EFFICIENT LOCALIZATION ALGORITHMS FOR WIRELESS GAS LEAKAGE DETECTION IN OIL/GAS INDUSTRY

BY

FARRUKH SHAHZAD

A Dissertation Presented to the

DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the

Requirements for the Degree of

DOCTOR OF PHILOSOPHY

In

COMPUTER SCIENCE AND ENGINEERING (CSE)

Dec. 2015

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS
DHAHRAN 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This thesis, written by **FARRUKH SHAHZAD** under the direction of his thesis adviser and approved by his thesis committee, has been presented to and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **DOCTOR OF PHILOSOPHY IN COMPUTER SCIENCE AND ENGINEERING (CSE)**.

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Dedication

This work is dedicated to my family for their support and patience during this endeavour. Thank you.

ACKNOWLEDGEMENTS

In the name of Allah, the Most Gracious, the Most Merciful.

All Praise is due to Allah, and peace and blessings be upon Prophet Muhammad and upon his family and his Companions.

I would like to acknowledge the support provided by the department of Information and Computer Science, and Computer Engineering and Deanship of Scientific Research at King Fahd University of Petroleum and Minerals (KFUPM).

First, I am thankful to my advisor, Dr. Tarek R. Sheltami, for his guidance, help, and support during this research. I am impressed by his great sense of care, respect and flexibility for his students. Many thanks are also due to my dissertation committee members Dr. Ashraf Mahmoud, Dr. Lahouari Cheded, Dr. Mahmood Niazi and Dr. Mohammad Alshayeb for spending their valuable time and providing useful comments and feedbacks.

I also like to appreciate my family, especially my wife, my parents, my children and my sisters for their prayers, support and encouragement.

Finally, I would like to thank all friends and colleagues who helped me in any capacity during my stay at KFUPM.

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THESIS ABSTRACT

NAME: Farrukh Shahzad

TITLE OF STUDY: Efficient Localization Algorithms for Wireless Gas Leakage Detection in Oil/Gas Industry

MAJOR FIELD: Computer Science and Engineering (CSE)

DATE OF DEGREE: Dec. 2015

The oil and gas industry includes processes for exploration, extraction, refining, transporting, and marketing petroleum products. This environment usually involves some type of hazardous substances including toxic and/or flammable gases. Gas leaks due to accidents or equipment malfunctions can cause severe danger to the plant, its employees and surrounding neighborhoods. The oil and gas industry therefore requires a comprehensive safety plan to deal with hazardous gas leakage, which includes early-warning devices such as gas detectors. Furthermore, government regulations to tackle industrial gas leakage are constantly changing and becoming stricter every year, hence the necessity for efficient and reliable gas detectors.

In this work, we survey most common industrial gases, their properties, gas detection sensors and the technology employed to deal with the gas leakage. We also provide a summary of research related to gas detection and monitoring conducted in the last 50 *years. According to researchers, wireless sensor networks (WSN) will be the only feasible solution for sensing in the oil and gas industry. Moreover, we explain the utilization of WSNs in the oil/gas industry and requirements/challenges of adapting WSN in such environment. Wireless sensors and devices have the ability to monitor the plant performance and the operational environment of oil, gas and resource production plants. One important research area in gas leakage detection using WSN is placement of sensors and determining the actual location of the leakage.*

As part of this research, we extend a simulation framework, written in Python, which is specially designed for wireless network simulation and add to it an interactive generic topology generator module. Our simulation framework also produces interactive charts, plots, and log all relevant simulation results for further analysis. We first generate multiple isotropic and anisotropic topologies of different shapes and then simulate localization algorithms and analyze the results statistically and visually.

Finally, we propose a new localization scheme, called DV-maxHop, that can reach better or comparable accuracy quickly utilizing simpler, practical and a proven DV-hop algorithm. Our enhanced localization scheme can easily be integrated with existing networks, which are using DV-hop based localization, with minor modifications. We evaluate the performance of our scheme using extensive simulation on several topologies under the effect of multiple anisotropic factors. Even for isotropic networks, our scheme out-performed recent state-of-the-art algorithms with lower computational overheads and reduced energy or communication cost due to a much faster convergence.

ملخص

تشمل صناعة النفط والغاز عمليات التنقيب والإستخراج والتكرير والنقل وتسويق المنتجات البترولية. هذه البيئة عادة ما تنطوي على نوع من المواد الخطرة بما في ذلك الغازات السامة أو القابلة للإشتعال. تسرب الغاز بسبب حوادث أو أعطال المعدات يمكن أن يسبب خطر كبير لحقول النفط وموظفيها والأحياء المحيطة بها. لذا تتطلب صناعة النفط والغاز خطة السلامة الشاملة للتعامل مع تسرب الغازات الخطرة، والخطة تشمل أجهزة الإنذار المبكر مثل أجهزة الكشف عن الغاز. علاوة على ذلك، الأنظمة الحكومية لمعالجة تسرب الغاز تتغير بإستمرار وأصبحت أكثر صرامة في كل عام.

في هذا العمل، قمنا بمسح الغازات الأكثر شيوعا في الصناعة وخصائصها، وأجهزة الاستشعار للكشف عنها والتكنولوجيا المستخدمة للتعامل مع تسرب الغاز. كما قمنا بتوفير ملخص الأبحاث المتعلقة بالكشف عن الغاز والرصد ، و التي أجريت في السنوات ال 50 الماضية. ووفقا للباحثين، فإن شبكات الإستشعار اللاسلكية سوف تكون الحل الوحيد الممكن للإستشعار في صناعة النفط والغاز. وعلاوة على ذلك، قمنا بتوضيح استخدام شبكات الاستشعار اللاسلكية في صناعة النفط والغاز والمتطلبات وتحديات التكيف للشبكات في مثل هذه البيئة.

أجهزة الاستشعار اللاسلكية لديها القدرة على مراقبة أداء المصنع والبيئة التشغيلية لمحطات النفط والغاز وإنتاج الموارد. وضع أجهزة الإستشعار وتحديد الموقع الفعلي حيث تسرب الغاز هي نقطة بحثية هامة في الكشف عن تسرب الغاز باستخدام شبكات الاستشعار اللاسلكية .

في هذا البحث، قمنا بتصميم برنامد محاكاة، بإستخدام لغة بايثون(Python).حيث تم تصميم هذا البرنامج خصيصا لمحاكاة الشبكة اللاسلكية وقمنا بإضافة وحدة مولد طوبولوجيا التفاعلية. برنامج المحاكة يولد الخرائط التفاعلية وجميع نتائج المحاكاة ذات الصلة لتحليل البيانات. نقوم أولا بتوليد طبولوجيات متعددة للخواص ومتباينة الخواص من مختلف الأشكال، ثم محاكاة الخوارزميات وتحليل النتائج إحصائيا وبصريا.

وأخيرا، قمنا باقتراح خوارزمي جديد لتحديد الموقع، وهو يسمى: "DV-MaxHop"، يمكن بواسطته أن نصل إلى دقة مقارنة أفضل. يمكن لمقترحنا الإندماج بسهولة مع الشبكات القائمة، والتي تستخدم خوارزمية "DV-hop" القائم، مع تعديلات طفيفة. قمنا بتقييم أداء مقترحنا باستخدام برنامج المحاكاة على عدة مخططات تحت تأثير عوامل متعددة متباينة الخواص. حتى بالنسبة لشبكات متباينة الخواص، تفوق على الخوارزميات الحديثة مع عمليات حسابية وطاقة مستهلكة وتكلفة الاتصال أقل بسبب التقارب السريع.

CHAPTER 1

INTRODUCTION

The industrial environment usually involves some type of hazardous substances including toxic and/or flammable gases. Accidental gas leaks can cause potential danger to the plant, its employees and the surrounding neighborhoods. The safety plan of most industries includes measures to reduce risk to humans and plant by incorporating early-warning devices such as gas detectors. Especially, for the oil and gas industry, leakage detection and localization are important tasks for any plant operation[1].

There are several processes which are involved in the oil/gas industry, from the initial drilling to the final marketing of the petroleum and its by-products. The main products include oil, fuel, and gasoline and provide several chemical products in the form of plastics, rubber, solvents, fertilizers and pesticides. Higher demand for fossil fuels means the industry will not only have to improve operations but also improve safety to increase productivity and expand business in the competitive world. Furthermore, the government regulations are getting stricter due to public environment awareness. The industry needs to develop new methods and adopts new technologies to abide by the ever-changing regulations without impacting production[2].

Fatalities, Injuries and damages related to accidental gas leak are not uncommon. The latest chlorine gas leak was reported in August 2015 in Spokane, WA (USA) injuring about 30 people. Fatalities are common in other under-developed populous countries such as India. The infamous Bhopal disaster in 1980's, San Bruno gas explosion in 2010, BP's Texas City refinery explosion in 2005, and explosion that destroyed the Deepwater Horizon drilling rig in the Gulf of Mexico (2010) are some of the high-profile incidents which made international headlines. Therefore, the need for an efficient, reliable and secure gas leakage detection systems is undisputed.

In the last 50 years, there has been extensive investigation in sensing technology for improved gas detection. Research has been focused on finding different approaches to tackle some of the inherent limitations of gas sensing technologies [3][4]. Since the evolution of digital wireless communication, gas sensing has received more attention from both industry and academia, for being a required component in any intelligent systems[3]. Gas sensing technology has been utilized in many common applications in areas such as Automotive industry, Medical equipment, Mining, Refineries, chemical plants, home safety, and Environmental studies.

1.1 WSN-based Leak Detection Solutions

Some approaches have been proposed recently for gas detection and monitoring using WSNs [5] [8]. One of the approach involves the application of low power sensors implemented using chemical sensing films. The sensor nodes employing the gas sensors of this kind are characterized by long term operation, but fail to meet the standard safety requirements on early gas leak detection. The another approach involves the application of power hungry spectroscopy based sensors on-board of autonomous WSN devices. These sensors can consume up to 500 mA, but are featured by high selectivity and fast response time that ensures safe and early hazardous gases detection.

In [6], authors proposed a wireless gas sensor network (WGSN) that employs an autonomous semiconductor gas sensors node. To increase the sensor sensitivity and selectivity, we have used a temperature scanning analysis mode for gas measurement, as well as the sensor sensitive layer heating in pulse mode. Experiments made with methane have shown that the system is able to accurately detect and measure the methane concentration in the atmosphere.

Same authors [7], performed several experiments on evaluation of quality of wireless links to ensure the safe delivery of sensor data and performed the analysis of the catalytic sensor response under various conditions in a real boiler facility.

James Weimer et al. [9], proposed an approach to leak detection using wireless sensor networks at carbon sequestration sites. By applying a basic linear dynamic model for an advection-diffusion process, a model-based detection strategy called the Iterative Partial Sequential Probability Ratio Test (IPSPRT) can be employed to detect and localize multiple leaks. A 3-D CO_2 transport model is employed to provide a proof of concept simulated evaluation of the IPSPRT against a windowed-average approach in terms of time-to-decision vs. probability of false alarm and probability of a missed alarm.

The authors in [16], describes the performance and functional characteristics of

PIC18LF4620 based wireless sensor node in monitoring the parameters such as CO_2, Oxygen, temperature, humidity and light around the pipeline structure. The system is deployed to monitor any deviations in these parameters with the standard atmospheric values eventually alert the user even to a remote location. The proposed system is a battery operated wireless sensor node which is interfaced with the external sensors to measure the parameters and the distance range between sensor node and coordinator node is also tested.

In [17], authors proposed a control system which is based on low power MSP430 microcontroller and Xbee techniques. The sensor node helps in collecting data regarding gas leakage and the particular area of sensor node address is located. The collected information is sent to the monitoring client or user to update the data. Data packets are continuously transmitted from sensor nodes and communication devices.

Apart from academia, some white papers were published by government agencies [10] [11]. However, wireless sensors are not mentioned in those documents. These documents provide review of some sensor technology and the study done for leak detection.

1.1.1 Efficient Localization Algorithms

Sensor data are often only meaningful when location and time of the readings are known [18]. To achieve this, not only sensors need to be time-synchronized with each other but also require that the absolute, relative or logical geographical position of sensors be known. The design of localization and time synchronization protocols is complicated by the lack of GPS receivers due to the cost, size and energy consumption of such devices. Often, only a few nodes will be equipped with GPS devices and the surrounding nodes have to determine their position from additional range or angle measurements and other algorithms or using trilateration iterations.

One of the key requirement for a gas leakage detection system is to determine the actual location where the leakage has occurred. This process of localization is a key issue in wireless sensor network based-solutions. The geographical location of sensors is an important information that is required in sensor network operations such as target detection, monitoring, and rescue. These methods are classified into two broad categories, namely range-based and range-free. range-based localization achieve high location accuracy by using specific hardware or using absolute received signal strength indicator (RSSI) values, whereas range-free approaches obtain location estimates with lower accuracy [19], [20]. Localization can be done by two distinct ways: The first one is distributed localization in which each node is able to localize itself, and the second one is centralized localization in which nodes send their data to a centralized unit, where data is processed to extract position information [21].

1.2 Problem Statement

As we can note from previous section that there is insufficient research conducted in the gas leakage detection monitoring using wireless sensor network specially in the oil/gas industry. There are many unanswered questions related to sensing technology, toxic substances which need to be detected, challenges in utilizing WSN for gas leakage detection and efficient methods or algorithms for detecting the location of gas leakage. Recent localization algorithms [22][23] [24] are focused on improving the localization accuracy without any efficiency consideration like energy cost and algorithm convergence time. We believe, we can achieve multiple objectives of good accuracy and efficient localization. This work is centered around studying and answering these questions.

1.3 Research Questions

RQ1: What are the challenges and the existing methods in gas leakage detection/sensing?

RQ2: Which of the existing localization algorithm is best suited for toxic gas detection?

RQ3: Which of the existing simulation tools we can use for localization algorithm evaluation and development?

RQ4: Can we develop a new localization scheme which can achieve multiple objective of accuracy and efficiency?

1.4 Research Objectives

The Research Objectives can be summarized as follows:

1. literature review to be conducted for the following to learn and study the existing methods and challenges in adapting WSN for gas leakage detection:

- Review of industrial gases and its properties, gas detection sensors and technology employed, and study of how these gases are monitored and detected in industrial environment.
- Survey of the previous work in WSN-based gas monitoring or leakage solutions.
- Survey of the existing localization algorithms and conducting a comparison study.

2. Select an appropriate simulation tool and extend it to support comprehensive study of localization algorithms.
3. A comparison study to be conducted via means of simulation of various localization algorithms.
4. Propose a new accurate and efficient localization scheme.
5. Development of a proof-of-concept interactive web-based gas leakage monitoring system using satellite technology.

1.5 Research Methodology

This research will be conducted in phases by dividing the work into tasks.

Phase I - Literature Review: Research will be conducted to discover the latest development in the area of industrial gases, sensing technologies, leakage detection, and adoption of WSN to detect toxic gases.

Phase II - Localization Algorithm Study: We will study and compare the existing localization algorithms.

Phase III - Simulation: In this phase, we will utilize and/or develop a simulation tool for WSN to study the performance of localization algorithms.

Phase IV - Algorithm Development: Based on the comprehensive simulation of the existing algorithms, propose a new efficient scheme for determining the location of gas leakage.

Phase V - Prototype Gas Leakage Detection System: Finally, we will design and develop a proof-of-concept web-based gas leakage detection system. We will utilize an internally-developed satellite monitoring system to report back the data from the sensors in the field and visualize and analyze the information.

1.6 Expected Outcomes

- A Study about the feasibility and challenges of utilizing WSN for gas leakage detection, including survey on existing technology related to gas sensors and its monitoring.

- An enhanced WSN simulation tool to support detailed simulation-based study of network algorithms.

- Implementation of existing localization algorithms and analysis of their simulation results.

- Comprehensive simulation and validation of the proposed efficient localization scheme.

- A Prototype WSN-based gas leakage detection system with an interactive web application to monitor/analyze the sensor data.

- Documentations and publications involving all the skills and expertise that has been gained during this research. We except to have at least one publication based on each item listed above.

1.7 Organization of the Dissertation

The rest of this dissertation is organized as follows. Chapter 2 provides a comprehensive review of the literature regarding industrial gases and its properties, the details of gas sensors and classification of sensing technologies, wireless sensor networks (WSN) technology and its feasibility for gas monitoring in the oil and gas industry and recent trends in gas detection and industrial adaptation of WSN. Localization in WSN including techniques, challenges, its significance in gas leakage detection and algorithms are discussed in chapter 3. In chapter 4, the simulation tool utilized in this research is introduced and an extension implemented by the author are presented with a simulation example . The algorithms that can be utilized for gas leakage detection in oil/gas industry are analyzed and a new efficient scheme is proposed, and its simulation results are analyzed in chapter 5. The proof-of-concept prototype and interactive web application are presented in chapter 6 with implementation details and web screen images. Finally, chapter

7 concludes the dissertation with the list of our contributions/publications and presents future directions.

CHAPTER 2

LITERATURE REVIEW

In this review, we shed some light on industrial gases and their properties in section 1. In section 2, we present the details of gas sensors and the classification of sensing technologies. In section 3, wireless sensor networks (WSN) technology and its feasibility for gas monitoring in the oil and gas industry is explored. finally, we provide recent trends in gas detection and industrial adaptation of WSN. We conclude in section 5.

2.1 Industrial gases and their properties

Gas is a state of matter, in which the molecules move freely and the whole mass can occupy the entire volume of any container as it expand indefinitely. Gases follow certain laws relating their conditions of volume, pressure, and temperature, which are called gas laws. Gases can be liquefied through compression or temperature reduction and mixed freely with other gasses. In this work, the term 'industrial gases' refers to any compressed gas or liquid used in manufacturing processes or present in a typical oil and gas industrial site. These industrial gases have a variety of applications as mentioned in the previous chapter. Generally, these gases are produced in a separate facility and then shipped and stored at the end users' facility.

2.1.1 Toxic Industrial Substances

In the modern industrial world, toxic industrial chemicals are extracted or produced, transported, stored and utilized everywhere, in any of the three states (solid, liquid or gas). These chemicals can be classified as either chemical/health hazards (e.g., carcinogens, corrosives, reproductive hazards or agents that affect blood or the lungs), or physical hazards (e.g., flammable, combustible, explosive, or reactive) or both.

The time that these agents persist in the environment (which can be hazardous to humans) is dependent on many factors:

- Physical state (solid, liquid, or gas),
- Quantity released.
- Weather conditions (wind speed, rain or snow, air or surface temperature),
- Release location either indoor or outdoor,
- Chemical stability of the substance, and
- Method of release (vapor or aerosol)

These chemicals can enter the body either through inhalation, the skin, or digestion. Usually, poisoning occurs more quickly if a substance enters through the lungs as the agent can rapidly diffuse throughout the body. Table 2.1 lists most common industrial gases, their physical properties and exposure limits [25]. This information is collected from different sources including oil/gas industry gas safety guidelines. Some of the critical exposure limits are described below:

Lower Explosive Limit (LEL) is the minimum concentration of a flammable gas or vapor that can propagate the flame when exposed to a ignition source. An increase in atmospheric pressure or temperature will reduce the LEL of a gas or vapor.

Upper Explosive Limit (UEL) is the maximum concentration of gas in the air that can combust. Increased amount of combustible gas or lower percentage of oxygen in the mixture will be too rich to maintain combustion.

TWA (time-weighted Average) is the summation of the exposure related to a particular toxic material measured in terms of ppmh (parts per million hours) and dividing it by an eight-hour period (i.e a normal working day).

STEL (Short-Term Exposure Limit) is an exposure measured as 15-minute time-weighted average. The exposure should not exceed this value at any time during a work day. There should be at least 60 minutes between successive exposures at the STEL and this exposures should not be repeated more than 4 times in an 8 hour shift.

IDHL (Immediate danger to life and health): Exposure beyond this limit can most likely cause death or immediate and/or delayed permanent adverse health effects. It can cause damaging effect to a person with inability to escape from the site of incident.

2.2 Gas Sensors

The authors of [3] classified gas sensing technologies into two categories, namely the methods based on variation of electrical properties and methods based on other kind of variations. Figure 2.1 shows four kinds of sensors under each category (interested researchers are advised to review this paper [3] for a comprehensive study of gas-sensing technology). The selection from this list depends on the many factors including application, cost and desired accuracy. Table 2.2 shows the summary of basic gas sensing methods [3]. The table also list advantages and disadvantages in employing these sensing technologies and target industry or application where they are suitable.

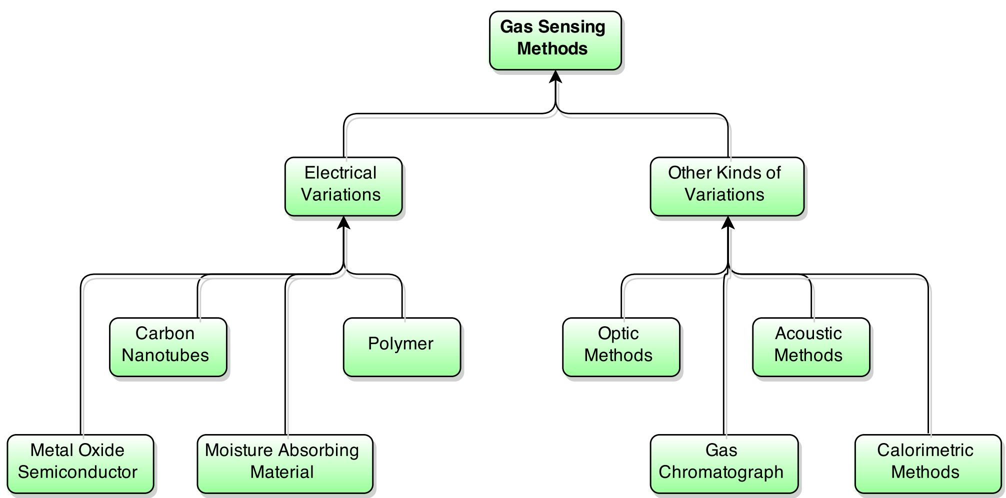


Figure 2.1: Gas Sensor Classification

The other factors or indicators that are considered to evaluate the performance of a gas sensor are listed below [3]:

- Selectivity, the ability of the sensor to distinguish a specific gas among a mixture;
- Sensitivity, the minimum concentration required for the detection of target gases;

- Reversibility: the ability of the sensing materials to return to its original state after detection;
- Response time: the time period needed to detect and generate a warning signal after gas concentration reaches a specific value;
- Adsorption capacity: the value of the amount of adsorbed substance reached in a saturated solution;
- Energy consumption: the amount of electrical power required to produce a stable reading;
- Fabrication cost per unit, including design, development and manufacturing cost.

The gas sensors should show a reproducible and stable signal for a time period, especially those which are designed to monitor mission critical equipments and facilities. Some of the factors that can lead to gas sensor's instability includes manufacturing errors, structural changes, phase shifts, poisoning triggered by chemical reactions and change in the surrounding environment.

2.2.1 Gas sensor Placement

The placement of gas sensors for leakage detection should be decided upon following the gas dispersion expert's advice. The input from safety and engineering personnel are also important. The agreement reached between the stack holders regarding the location of detectors should be written down for future discussions. Generally, gas detectors are installed where the gas leakage is most likely to happen. In an industrial plant, this would be the area around compressors, storage tanks, boilers, cylinders and pipelines especially near parts such as valves, flanges, T-joints, gauges,, filling or draining connections etc. There are a number of obvious and common-sense considerations that help to determine the most appropriate gas detector location:

1. Follow the manufacturer's recommendation.

2. Detectors should be mounted at a low level to detect gases that are heavier than air (e.g. Butane and Sulfur Dioxide).

3. Gas detectors should be mounted at high level with a collecting cone to detect lighter gases (e.g. Methane and Ammonia).

4. Cover the detector with a sunshade if used in a hot climate and in direct sun or use weather protection assembly for outdoor installation.

5. Detectors should be placed such that any leak of gas should not pass by in a high speed jet and remain undetected i.e some short distance away from high pressure parts.

6. Detectors should be installed at the designated location with the detector pointing downwards to protect against dust or water.

7. It is important to ensure that there is no permanent obstruction of the IR beam, when siting open-path infrared devices. Blockage due to vehicles and personnel can be accommodated.

8. Ensure that the mounting structures are sturdy and vibration-free.

9. Use engineering judgment based on the risk of gas leakage and facility layout.

10. Consider ease of access for functional testing and future servicing.

Some other factors which can help in selecting the most appropriate location for placement of gas sensors include:

1. Purpose of gas detection system, whether for leakage, area or human protection monitoring;

2. Type of gas available, whether flammable, toxic and/or liquefied;

3. Ambient conditions, like temperature, pressure, humidity;

4. Minimal vibration, shock and mechanical stress;

5. Lower Electromagnetic Interference (EMI);

2.3 Gas Sensor Monitoring

The gas sensor monitoring can be classified into two broad categories, namely: Wired network of sensors, and Wireless sensor network (WSN).

In a conventional system, an array of sensors are wired together to form a network of sensors which may include one main power supply. This system usually can have powerful hardware, due to unlimited, always-on power, including powerful gas sensors, and digital signal processor (DSP) for real-time processing [1]. Wired gas-monitoring systems have disadvantages related to difficulties with wiring, vulnerability, high maintenance cost and inflexibility of wired communications. Moreover, in case of monitoring gases with different densities, it is necessary to install sensors at various height levels, which leads to extra troubles with wiring. In contrast to wired solutions, wireless systems can be more suitable and flexible for the task of continuous environmental monitoring in large areas. A wireless network of sensors provide a feasible alternative with low maintenance cost and eliminates wires almost completely. A typical wireless sensor network consists of a mixture of sensing nodes, relay nodes and a network coordinator (or sink or base station). A sensor node consists of a sensor (like gas sensor), micro-controller, RF transceiver and a battery.

Wireless sensor networks have brought about low cost, large-scale advanced remote monitoring and automation applications to the oil and gas industry. In addition to lowered initial costs and reduced operating expenses, WSN provides improved reliability, increased installation flexibility, and scalability to wireless sensor networks. It has made numerous monitoring applications that are feasible and which were previously not possible due to remote and hazardous environments. By 2020, it is expected that WSN will be ubiquitous in refineries, pipeline operation, exploration and production, retail and transportation. According to a recent report [26], WSNs will be the only feasible sensing solution for oil/gas industry. The survey found that over half of the company surveyed are involved with oil and gas and 8% of the end users have deployed over 1,000 wireless field devices. The exploration, production and pipelines made up 27% of the global industrial WSN market in 2011. WSN technology is ideal for this industry for the following reasons:

1. The sites are remote, widely spread out and hazardous,

2. The cost and effort required for installation of new wired devices are high,
3. Sometime temporary sensor installation is required for evaluation only, hence does not justify the high installation cost and effort of a wired device.
4. Sensor redundancy is required for fail-proof operation and leakage detection,
5. The new state-of-the-art control solutions require new sensors,
6. The demand for continuous production optimization and improved safety.

The WSN solution also provides remote monitoring options for the industry to meet regulatory and production demands [2]. The Following remote monitoring applications can use WSN-based solutions:

1. Tank Level Monitoring
2. Wellhead Automation and Monitoring
3. Pipeline Integrity Monitoring
4. Pipeline Pressure Relief Valve Monitoring
5. Equipment Condition-based Monitoring

There has been plenty of work/research in different aspects of WSN technology [27][28] since 2000. WSN has been utilized in almost any imaginable application in all types of environments with mixed results [29][30][31].

2.3.1 WSN Requirements in Oil/gas industry

Due to the nature of the Oil & Gas industry, the following technical requirements should be met for WSN deployment [32].

Open standardized systems

It is highly desirable to use standardized and open communication systems as compared to proprietary systems. The standardized solutions provides the freedom to choose between suppliers and usually have a much longer lifespan than proprietary solutions. Several devices and applications can utilize the same wireless infrastructure. On the contrary, the standardized solutions may have published security mechanism, making it somewhat more vulnerable to attacks. Also the adaptation of international standards is a slow process, and therefore proprietary solutions may enter the market earlier [21].

Low-power operation for Longer system lifetimes

The effort required to replace the batteries or in some cases the whole sensor itself (if the battery is encapsulated) means that the Oil & Gas industry is demanding longer battery lifetimes for wireless sensors. They are advocating for at least five years of continuous operation (with update rate of one minute), otherwise a huge effort would be necessary simply to maintain the network as it is expected that hundreds of wireless sensor nodes could be deployed in a single facility [33], [34].

This means that the sensor must be able to go into a low-power mode to ensure long battery life and uninterrupted operation. This challenge of operating at low-power sleep mode and at the same time always be available requires that all nodes to be time-synchronized so that they can wake up later at a correct time [35][36][37]. Longer battery life also requires employing efficient message routing and MAC protocols to optimize network traffic in terms of hop counts and low re-transmission rate [38][39][40].

Seamlessly work with existing communication systems

In recent years, several types of communication infrastructure including WLAN have been incorporated in the Oil/Gas sector to provide continuous round-the-clock monitoring and control of the assets and to link onshore control centers with offshore systems. It is vital that any new system like WSN solutions should coexist with other communication systems so it can be successfully adopted by the Oil/Gas industry. This means no interference between WLAN and WSN and robust operation of all existing systems when installed within the same neighborhood.

Measurable network/system performance

The environmental changes can effect the performance of wireless networks more than their wired counterparts. The expectation is that a WSN solution should at least meet (if not exceed) the performance of existing wired solutions. The quality of a wireless link should not be affected by trivial things like moving assets or workers and not even by environmental fluctuations in humidity, wind speed and temperature. There have been several techniques proposed and implemented to improve the overall performance of a WSN-based system.

Security

The wireless data transmission can be tapped into easily as compared to wired transmissions and this makes it easily for hackers to eavesdrop on the information or perform security attacks. Several research studies can be found in academia to employ encryption techniques to provide data privacy, whereas access threats are counteracted by performing data consistency validation and by using transmitter authentication methods [41].

Other challenges

Apart from the above requirements, there are many other challenges related to the utilization of wireless devices in the oil/gas industry[2]. It should have:

- appropriate size, shape and construction;
- designed as a self-contained unit;
- the ability to seamlessly integrate with existing monitoring and control solutions;
- the ability to self-reconfigure, be fault-tolerant, dynamic and adaptive;
- the ability to utilize open, international standards;
- enough processing power, storage/memory, battery power and monitor size (if any). This means the system should be able to execute complex network algorithms with real-time requirements and adaptive routing protocols;
- the ability to operate in hostile areas where environmental and platform conditions may be very harsh;

- services to support dynamic system environment;
- the option to operate in the unlicensed region of the frequency spectrum;
- scalability i.e. the ability to grow in number of nodes and capabilities as the demand grows.

2.4 Recent Trends in gas detection systems and WSN

In recent years, there have been significant interest in the design and development of 'e-Nose' sensor network [42], which could be utilized for gas detection [43] as they offer an excellent discrimination and can lead the way for a new generation for gas sensors. The e-Nose terminology is commonly associated with electronic system devices by using an array of sensors and works like a human 'nose' to recognize or detect odor and flavor. The classical e-Nose system is still in common use despite recent advancements in this area.

To maximize the lifetime of the wireless sensor node-based systems, several techniques have been proposed including routing and data dissemination protocols, tiered system architectures, energy-aware MAC protocols [44][45][46], duty-cycling strategies, power-aware storage, and adaptive sensing rate . In future, it is forecast that fewer nodes will be equipped with batteries. It is expected that the majority of the WSN nodes will be relying on energy harvesting [47][48]. Energy Harvesting-based WSNs (EHWSNs) operates by extracting energy from the surrounding environment. Energy harvesting can exploit different sources of energy, such as solar power, wind, mechanical vibrations, temperature variations, magnetic fields, etc. If the harvested energy source is large and periodically or continuously available, a sensor node can be powered perpetually [49][50].

With the success of WSN application in consumer market, attention has recently turned to development of WSN systems for mission-critical industrial environment. Therefore, a notable trend in industrial automation in recent years has been the replacement of wired communication with low-power and low-cost wireless sensor and actuator networks. Andreas Willig in his paper [18] pointed out several issues about the proper design of networks and protocols for industrial wireless sensor network (IWSN), including providing the required QoS in terms of reliability, MAC protocol design, error-control schemes, routing and transport protocols, application-layer protocols, hybrid wired/wireless systems, mobility support, security and privacy, energy consumption and energy-efficient design and scalability. A typical wireless industrial automation network deployment consists of field devices equipped with sensors and actuators that communicate with the plant network. Industrial automation applications usually have three types of data traffic: safety, control and monitoring (in order of priority). One of the key requirement for an industrial wireless system is to enable high-priority traffic to hijack the transmission bandwidth of the low-priority traffic, when needed.

To overcome the shortcoming of the WSN communication protocols in the harsher industrial setup, a series of industrial standards like WirelessHART, ISA100.11a, IEEE 802.15.4e, and WIA-PA have been released in recent years. These standards leverage the IEEE 802.15.4 physical layer with a low-rate of a maximum of 250 kbps and a low implementation complexity for simple devices. They utilize the TDMA mechanism to provide guaranteed access to the wireless medium and adopt packet-level channel hopping to improve the reliability of individual wireless links by combating external interference. They also support priority-based schemes to access the medium for message delivery [51].

The author of [18] concluded that there is huge potential for research in wireless communication systems designed for industrial environment. One source of this effort is the adoption of the communication technologies like WSN or UWB technologies, another source is to identify promising approaches from the wireless and networking community like cooperative diversity schemes. The challenges and opportunities are not only in the design of protocols leveraging these approaches, but also in the systematic development of the methodologies and tools necessary for the proper planning and configuration of wireless industrial sensor networks.

2.4.1 Industrial WSN

Industrial Wireless Sensor Network (IWSN) evolved from WSN and are specially designed keeping in mind the demands and nature of industry [52]. IWSNs use replaceable batteries and generally have wider range than WSNs. IWSNs have an edge over traditional wired structures since they can be installed easily anywhere in industry without heavy support structures. IWSNs can also work efficiently where wired networks are technically not installable such as on moving or rotating objects. Another important industrial requirement is the stability of the system. The system should be stable and easy to handle and maintain [52]. Also, deployed networks should be reliable and secure with high data rate support. Many protocols are developed that support the above functionalities.

- Zigbee is a wireless open global standard which satisfies the unique needs of low-power, low cost and wireless mobile-to-mobile (M2M) networking. It is also used in IWSNs [53]. Zigbee is standardized by Zigbee alliance which consists of more than 300 companies. It can support star, mesh and tree topologies [54].

- Another developed protocol is Highway Addressable Remote Transducer Protocol commonly known as WirelessHART and approved by International Electrotechnical Commission (IEC). WirelessHART is simple, secure, reliable, and uses TDMA with mesh topology. HART, like OSI model, uses many layers that add to security, integrity and reliability of the system [55]. The power consumption of HART is low compared to Zigbee with high security standard.

- ISA100, designed by the International Society of Automation, supports high data rates up to 250 Kbps. Security and Integrity is provided by layered architecture. 6LoWPAN, used in network layer, provides efficient routing and also enables IWSN to co-exist with other IWSN protocols. At the level of Physical Layer, IEEE 802.15.4 is used which employs Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA). ISA works on 2.4 GHz free band with 16 channels. Transmitter complexity is significantly decreased by using Orthogonal Quadrature Phase Shift Keying (O-QPSK), which avoids the zero state and thus has a constant envelope transmission [56].

2.5 Conclusion

In this survey, we presented the information related to industrial gases monitoring and sensors employed in the context of leakage detection. We also provided details of how these gases are monitored and detected in an industrial environment and their significance. We explained the utilization of WSNs in the oil/gas industry and requirements/challenges of adapting WSN in such environment. Wireless sensors have the ability to monitor the performance and the operational environment of plants involving oil/gas. A well-designed, developed and deployed sensor solution promotes a safe and healthy workplace and simultaneously can optimize production and operational safety. Wireless sensor solutions can further provide benefits such as optimized operations, error tolerance, problem prevention, and reduction of operating costs. It is expected that these cost-effective wireless solutions will soon be deployed in remote and/or hazardous areas in the oil/gas industries. The recent advancement in industrial wireless sensor networks includes the availability of low-power gas sensors, e-nose technology, release of industrial wireless communication standards, and research in different aspects of industrial wireless automation. Our review shows that there is not enough research conducted in the gas leakage detection using wireless sensor networks in the oil and gas industry, specially in academia.

Table 2.1: Industrial Gases' Properties

Substance	Formula	Physical properties	Industry	Exposure Limits
n-Butane	C_4H_{10}	Colorless gas Gasoline like odor Combustible	Propellant filling Docks Tanks filling docks	STEL: 1 ppm TWA: 5 ppm (OSHA) LEL: 1.6% by volume
Ammonia	NH_3	Colorless gas Pungent odor	Semiconductor Fertilizer Water treatment plants	STEL: 35 ppm TWA: 50 ppm IDLH: 300 ppm LEL: 15% by volume
Benzene	C_6H_6	Colorless liquid aromatic odor	Refineries Oil/gas distribution Gas stations	STEL: 2.5 ppm TWA: 0.5 ppm LEL: 1.2%
Carbon Dioxide	CO_2	Colorless gas odorless	Dry ice plant Oil well injection Mushroom farms stack gas Oil well injection	STEL: 30,000 ppm TWA: 5000 ppm IDLH: 40,000 ppm
Carbon Monoxide	CO	Colorless gas Odorless Most abundant toxic gas	Furnaces gas generator/engines Mining, Parking garages	STEL: 200-400 ppm TWA: 50 ppm IDLH: 1200 ppm LEL: 12.5%
Chlorine	Cl_2	Green-yellow gas Pungent odor	Water treatment plants Mining PVC manufacturing	STEL: 0.3 ppm TWA: 0.1 ppm IDLH: 5 ppm
Hydrogen	H_2	Colorless gas combustible	Battery charging stations Vegetable oil plants	LEL: 4% There are no specific exposure limits
Hydrogen Cyanide	HCN	Colorless gas Bitter almond-like odor	Plating and Mining Nylon Manufacturing	LEL: 5.6% TWA: 10 ppm IDLH: 50 ppm
Hydrogen Sulfide	H_2S	Colorless gas Rotten eggs odor	Mining/Metal industries Oil fields & refineries	LEL: 4.0% TWA: 20 ppm IDLH: 100 ppm
Methane	CH_4	Colorless gas odorless	Oil/gas distribution Refineries Mining	LEL: 5% No exposure limits
Nitric Oxide	NO	Colorless gas	Semiconductor plants Mining	LEL: 4.0% TWA: 20 ppm IDLH: 100 ppm
Nitrogen dioxide	NO_2	Reddish brown Pungent odor	Boilers & furnaces Diesel Emissions Semiconductor plants	STEL: 1 ppm TWA: 5 ppm IDLH: 20 ppm
Propane	C_3H_8	Colorless gas odorless	Aerosol Propellant filling lines Propane power forklifts	LEL: 2.1% TWA: 1000 ppm IDLH: 2100 ppm
Sulphur Dioxide	SO_2	Colorless gas Pungent odor	Diesel Emissions Water treatment Paper mills	STEL: 5 ppm TWA: 2 ppm IDLH: 100 ppm

Table 2.2: Standard gas sensing methods

Substance	Pros	Cons	Target Applications
Metal Oxide Semiconductor	Low cost Short response time Wide range of target gases Long lifetime.	Rel. low sensitivity/selectivity Sensitive to environmental factors High energy consumption	Industrial/civil applications
Carbon Nanotubes	Ultra-sensitive Great adsorptive capacity Quick response time Low weight	Difficulties in fabrication High cost	Detection of partial discharge
Moisture Absorbing Material	Low cost Low weight High selectivity to water vapor	Vulnerable to friction Pot. irreversibility in humidity	Humidity monitoring
Calorimetric Methods	Low cost Stable at ambient temp. Adequate sensitivity	Risk of catalyst poisoning Intrinsic deficiencies	Petrochemical plants Mine tunnels
Polymer	High sensitivity Low energy consumption Fast response time Low fabrication cost Simple structure	Long-time instability Poor selectivity Irreversibility	Indoor air monitoring Synthetic products' storage Chemical industries
Optical Methods	Long lifetime Insensitive to environment	Difficulty in miniaturization High cost	Remote air quality monitoring, Gas leakage detectors
Gas Chromatograph	Excellent separation performance High selectivity/sensitivity	High cost Difficult to miniaturize	Typical laboratory analysis
Acoustic Methods	Long lifetime Avoids secondary pollution	Low sensitivity Sensitive to environment	Components of WSN

CHAPTER 3

LOCALIZATION IN WIRELESS SENSOR NETWORKS

In a typical wireless sensor network (WSN), nodes are coupled to the physical world and have spatial relationship with other objects. In this context, localization in a WSN can be defined as the collection of techniques and mechanisms to measure the spatial relationship between nodes and physical objects. In other words, localization is a problem of estimating the location of an object with respect to a reference frame or some other reference object. The use of a Global Positioning System (GPS) receiver on each node (to have absolute coordinates) is unrealistic in the context of a usual WSN deployment in terms of node's limited size/hardware and power. Also GPS receivers have degraded performance in indoor places and in dense urban areas (need unobstructed view of sky to work reliably) [19][57], and are relatively expensive. Therefore, sensors and the communication systems in the node need to self-organize to accomplish a local/relative coordinate system.

Localization is an important part of WSNs design. In many applications, the information sent by a sensor node is of little use without any knowledge of the location of the sensor. Not only is it needed to report data that is geographically meaningful but it is also required for services such as geographical and context-based routing protocols, location-aware services, object or target tracking, coverage area management and disaster event notification (like gas leakage detection).

In this chapter, we review some of the concepts and technologies related to the localization in WSN. We present some of the commonly employed localization algorithms and discuss its applicability in the oil/gas industry and gas leakage detection.

3.1 Background

The locations of sensor nodes can be directly obtained by setting the coordinates manually (via pre-configuration) which requires that each sensor node be placed at a known location, which is only suitable for the case where sensor nodes are easy to be placed and their number is small [58]. On the other hand, in a typical outdoor setup, the node's absolute location can be determined by installing GPS receivers on each node. GPS is the most widely used location-sensing system which uses lateralization to obtain geographical location (latitude and longitude). It was established in the late 80's as Navigation Satellite Timing and Ranging or NAVSTAR. Currently, the fully operational (since 1995) global navigation satellite system (GNSS) consists of at least 24 geosynchronous satellites orbiting above the earth at around 11,000 miles.

However, a GPS-equipped wireless node is costly, power-hungry and need a clear view of sky to work [59], making it unrealistic for low-cost wireless sensor network systems. Therefore, the researchers have been focusing on solutions which can induce node locations by interactions through neighbor nodes. The distance estimation phase involves measurement techniques to estimate the relative distance between the nodes. The algorithms for position computation determine the coordinates of the unlocalized node with respect to the location-aware landmark nodes or other surrounding nodes.

Generally speaking, a localization algorithm manipulates the information related to distances and positions, to compute or estimate the location of most, if not all, of the WSN nodes. The localization process may also involve other methods and schemes to have more accurate node position by eliminating errors in distance estimation. Wireless sensor network localization algorithms can be categorized as follows:

1. Target/Source vs Node self localization,
2. Centralized vs Distributed,
3. Range-free vs Range-based,
4. Anchor-free vs Anchor-based,
5. Mobile vs Stationary

There are many survey papers which shed light on these categories of localization algorithms [59][60][61][21] [62][63]. For this work, we will focus on anchor-based range-free node localization as that only utilizes connectivity (neighbors) information for node localization and doesn't requires any special hardware for measurement (as opposed to range-based localization).

3.1.1 Target/Source vs Node self localization

The source localization is needed for several types of applications. In the outdoor scenario, aircraft or vehicle position estimation is an example of source localization. Similarly, it can be employed to locate marine species and ships. In an indoor environment, this scheme could track mobile assets or even humans. The target or source localization can be classified into either single-target localization or multiple-target localization [61].

3.1.2 Centralized vs Distributed

In centralized algorithms, all computation is done at a server or at a base station and are most likely to provide accurate location estimates. On the other hand, in distributed algorithms estimation process is distributed among the nodes [61]. Generally speaking, decentralized or distributed localization algorithms tend to be more complex than centralized algorithms and requires multiple iterations to reach an acceptable solution. However, distributed localization algorithms are scalable and implementable on larger wireless sensor networks. Centralized algorithms are usually more complex and less reliable due to single point of failure and the losses incurred because of the nature of multi-hop transmission through the wireless network [61].

3.1.3 Range-free vs Range-based

The range-free techniques use local and hop-counting methods for position estimation and recent research is mostly geared towards multi-hop range-free localization algorithm as that only utilizes connectivity(neighbors) information as opposed to ranging techniques which may be accurate but are expensive and limited [21].

A range-based system uses one of the ranging methods for distance estimation:

1. Angle of Arrival(AoA) method allows each sensor to evaluate the relative angles between two received radio signals.

2. Time of Arrival(ToA) method tries to estimate distances between two nodes using time-based measures.

3. Time difference of arrival(TDoA) is a method for determining the distance between a mobile station and nearby synchronized base station.

4. Received Signal Strength Indicator (RSSI) techniques are used to translate signal strength into distance.

Among the above, RSSI methods are easier to implement because the RSSI value can be read from the radio chip. However, RSSI is affected by the surrounding environment and the error of this ranging technique may be up to 50%.

Many localization algorithms first use a ranging technique to estimate the Euclidean distances between nodes, and then use the least-squares trilateration to determine the locations of sensor nodes by these estimated distances. Position estimates by lateration techniques are based on the precise measurements from three non collinear anchors. Lateration with more than three anchors called multilateration. Similarly, angulation or triangulation is based on information about angles instead of distance [22].

3.1.4 Anchor-free vs Anchor-based

Anchor Nodes are nodes that know their coordinates a priori by use of GPS or manual placement. For 2-D localization and 3-D localization, at least three and four anchor nodes are needed, respectively. In anchor-based approach, anchor nodes are used to calculate global coordinates for other nodes. In anchor-based localization algorithms, the location of each sensor node is determined only by its distances from anchors. In this work we will focus on anchor-based localization algorithms [58].

In Anchor-free approach relative coordinates are used. The location of each sensor node is determined also by the distances between sensor nodes. Research in this direction is utilizing semidefinite programming (SDP) and multidimensional scaling (MDS) techniques.

In Mobile-assisted localization, mobile agents or nodes are utilized to improve the localization accuracy. Mobile nodes (with GPS) rides through the network and help other sensor nodes to estimate the distance between them.

3.2 Significance of Localization in gas leakage detection

Position information plays a pivotal role in wireless sensor network (WSN) applications and protocol/algorithm design. In recent years, range-free localization algorithms have drawn much research attention due to their low cost and applicability to large-scale WSNs. However, the application of range-free localization algorithms is restricted because of their dramatic accuracy degradation in practical anisotropic WSNs, which is mainly caused by large error of distance estimation. Distance estimation in the existing range-free algorithms usually relies on a unified per hop length (PHL) metric between nodes. But the PHL between different nodes might be greatly different in anisotropic WSNs, resulting in large error in distance estimation. We find that, although the PHL between different nodes might be greatly different, it exhibits significant locality; that is, nearby nodes share a similar PHL to anchors that know their positions in advance.

3.3 Summary of existing Localization Algorithms

There have been significant efforts since 2000 to develop an accurate and reliable range-free localization scheme. Most of the early work assumes isotropic topology or regular homogeneous node deployment and achieve acceptable performance for most application. However, real-world deployments are usually in irregular areas with few holes or structures which cause packets to be detoured[64]. This is also true for industrial and urban infrastructure monitoring applications.

The distance vector or DV-Hop [22], Amorphous [65], MDS-MAP [66] and APIT [67] are examples of early range-free localization scheme well suited for isotropic wireless network. DV-Hop and Amorphous landmark work provide the basic technique to estimate the distance between nodes and many improvements were published since then [68][69][70][71][72]. However, in anisotropic network, DV-Hop and Amorphous distance estimation accuracy is severely degraded resulting in overall unacceptable localization errors.

The i-Multihop estimator proposed by Wang and Xiao[72] can recognize and filter out largely erroneous distance estimations and achieve higher accuracy. The snap-inducing shaped residual (SISR) estimator developed in [73] is applicable to cases in which distance estimations are either very accurate or contain very large error.

Another approach is correcting the obtained distance estimations before using them to calculate node positions in anisotropic network [74][64][71][72]. The Proximity Distance Mapping (PDM) [71] algorithm replaces the PHL with a proximity-distance mapping matrix to estimate the distance between nodes and anchors. Although improving the distance estimation accuracy, the PDM algorithm incurs a much higher communication cost than the DV-Hop algorithm. The REnded Path (REP) algorithm [74] exploited the geometric feature of the network to rectify the distance estimation of detoured paths. It has been shown that different anchor combinations will affect the localization accuracy. In [75], Shang at. al. proposed a simple heuristic algorithm that uses the four nearest anchors to perform localization. The algorithm, however, fails to utilize the anchors' redundancy to reduce localization errors.

The authors of [64] propose a pattern-driven localization scheme (PDS) by applying different distance estimation algorithms for anchors based on their exhibiting patterns. They compare it with Amorphous [65] and PDM [71]. In PDS algorithm, three different patterns are identified and nodes in different patterns use different methods to rectify the obtained distance. These algorithms first adopt DV-Hop or Amorphous to obtain the distance between nodes and then perform rectification. Locality-based distance estimation approach could be integrated into these algorithms as a replacement of DV-Hop or Amorphous.

One of the state-of-the-art scheme is reliable anchor-based localization (RAL) [23]. The idea is to reduce localization errors by ignoring the adverse effect of unreliable anchors whose path is detoured by obstacles and use only reliable anchors to perform localization. Each node will determine its own set of reliable anchors. One drawback is that the algorithm requires a lookup table, which need to be computed offline based on the sensor density, hop count and degree of radio irregularity (DOI). Also it requires some complex computation when compared to DV-hop.

Recently, anchor supervised locality-based approach was presented in [24], where every anchor selects a set of friendly anchors (local) to be used for distance estimation. This will eliminate the estimation error caused by other anchors and claims 30% or more, accurate results. However, the paper failed to show if the proposed algorithm is better than RAL or PDS (both of which provide better accuracy).

CHAPTER 4

SIMULATION TOOLS

Wireless Sensor Networks (WSNs) have been employed in many important applications such as intrusion detection, object tracking, industrial/home automation, smart structures and several others. The development of a WSN system requires that the design concepts be first checked and optimized using simulation [76].

The simulation environment for WSNs can either be an adaptive development or a new development. The adaptive development includes simulation environments that already existed before the idea of WSNs emerged. These simulation environments were then extended to support wireless functionality and adapted for use with WSNs. In contrast, new developments cover new simulators, which were created solely for simulating WSNs, considering sensor specific characteristics from the beginning [77]. Recently, several simulation tools have appeared to specifically address WSNs such as NS3, Cooja and Castalia [78], varying from extensions of existing tools to application-specific simulators. Although these tools have some collective objectives, they obviously differ in design goals, architecture, and applications abstraction level [76].

Simulators can be divided into three major categories based on the level of complexity:

- algorithm level,
- packet level, and
- instruction level.

Some algorithm level simulators are described in [79], [80], [81] and [82].

Simulation has always been very popular among network-related research. Several simulators have been developed to implement and study algorithms for wireless networks. Some are general-purpose while others are designed for a specific purpose and vary in features and level of complexity. They support certain hardware and communication layers assumptions, and provide a set of tools for deployment scenarios, modeling, analysis, and visualization. Classical simulation tools include NS-2/3, OPNET, OMNeT++, J-Sim, and TOSSIM [77][83][78].

For our research, we require an algorithm-level extensible simulation tool which can seamlessly support latest visualization and statistical libraries to perform state-of-the-art localization simulation in WSN. We found that none of the existing tool fulfill our requirements and require manual processing or extraction of simulation results for interactive analysis.

4.1 Pymote

After some research, we have concluded that a simple Python-based tool completely fulfill our requirements. We decided to use Pymote, a recent tool, which is a high level Python library specifically designed for wireless networks to perform event-based simulation of distributed algorithms [84]. The user can implement their ideas in Python; which has become popular in academia and industry. The library is developed without much abstraction and therefore can be used or extended using Python's highly expressive native syntax. The library particularly focuses on fast and accurate implementation of ideas at the algorithm level using a formally-defined distributed computing environment.

Following is a simple python script for simulating 'Flood' message among few nodes using Pymote. Figure 4.1 shows the generated topology.

```python
from pymote import *
net_gen = NetworkGenerator(degree=2, n_count=10)
#net = net_gen.generate_random_network()
#net = net_gen.generate_neigborhood_network()
net = net_gen.generate_homogeneous_network()
from pymote.algorithms.broadcast import Flood
net.algorithms = ( (Flood, {'informationKey':'I'}), )
some_node = net.nodes()[0]
some_node.memory['I'] = 'Farrukh'
sim = Simulation(net)
sim.run()
net.savefig(fname=__name__)
```

4.1.1 Why Python

1. Easy to learn, well documented and quick prototyping;

2. Full featured object-oriented language;

3. Python is expressive and simple which keeps the program/script easy to follow and use;

4. Support for interactive mode allows experimentation and analysis (Ipython);

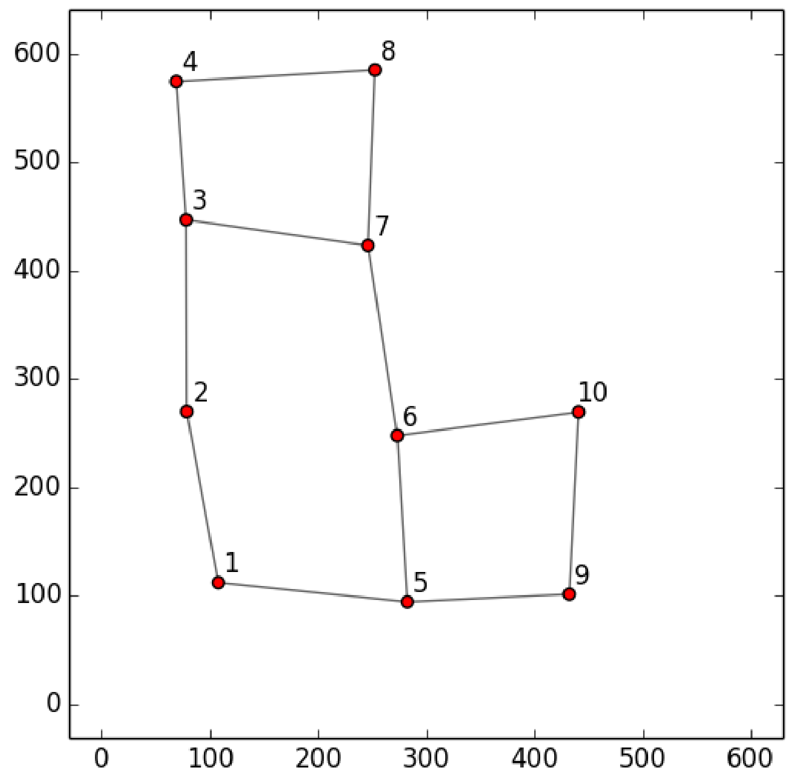


Figure 4.1: A simple 10-nodes WSN topology using Pymote

5. Python has great libraries to perform complex calculations and scientific computing (NumPy and SciPy, matplotlib);

6. Promote open-source reproducible research.

4.1.2 Pymote Features

1. Pymote is a Python package for event-based simulation and evaluation of distributed algorithms [84].

2. Pymote is designed to quickly develop and test new algorithms.

3. Current implementation is targeted towards wireless sensor network.

4. It is designed to be extended easily.

5. It is available as an open-source project.

4.2 Pymote Extension

In this section, we explain one of our contributions related to this research which is the design and implementation of packet-level modules for propagation, energy consumption and mobility models (at the physical layer) to extend the Pymote framework. We also added graphing and data collection modules to enhance the Pymote base functionality and modified existing modules for node, network, algorithm and logging.

4.2.1 Propagation Model

We implemented two basic radio propagation models and the commonly-used shadowing model for WSN in the Pymote framework. These models are used to predict the received signal power of each packet. At the physical layer of each wireless node, there is a receiving threshold (P_RX_THRESHOLD). When a packet arrived at a node, its signal power is compared with P_RX_THRESHOLD, and if it is below, it is assumed as lost by the MAC layer. The free-space propagation model assumes line-of-sight path between the source and destination nodes, while the two-ray ground reflection model also take into account the ground reflection path apart from the direct path. This means that it provides more realistic prediction at a long distance. However, in reality, the received power is a random variable due to multi-path propagation or fading (shadowing) effects. The shadowing model consists of a path loss exponent and a Gaussian random variable with zero-mean and standard deviation (σ_{DB}), which represent the variation of the received power with distance. Table 4.1 lists parameters available for propagation module. The propagation model type (free-space, two-ray ground or shadowing) is a network level attribute, which should be selected before starting the simulation.

Description	Parameter	Default
Transmit Antenna gain	G_TX	1
Receive Antenna gain	G_RX	1
System Loss	L	1
Min. Received signal power threshold	P_RX_THRESHOLD	-70 dbm
Frequency	FREQ	2.4 Ghz
Path loss exponent	BETA	2.5
Gaussian noise standard deviation	σ_{DB}	4 dbm

Table 4.1: Propagation model parameters

4.2.2 Energy consumption Model

In our extended framework, the energy model object is implemented as a node attribute, which represents the level of energy in a node. Each node can be configured to be powered by external source (unlimited power), Battery (default) or energy harvesting (EH) sources. The energy in a node has an initial value which is the level of energy the node has at the beginning of the simulation. It also has a given energy consumption for every packet it transmits and receives which is a function of packet size, transmission rate and transmit (receive) power. The model also supports idle or constant energy discharge due to hardware/ micro-controller consumption and energy charge for energy-harvesting based WSN. During simulation, the available energy of each node is recomputed every second based on the charging and/or discharging rate. If it drops below the minimum

Description	Parameter	Default
Transmit power	P_TX	84 mW
Receive power	P_RX	73 mW
Initial Energy	E_INIT	2.0 Joules
Min. Energy required for operation	E_MIN	0.5 Joules
Charging rate (EH nodes)	P_CHARGING	2 mW/sec
Discharging rate	P_IDLE	0.1 mW/sec
Transmission rate	TR_RATE	250 kbps

Table 4.2: Energy model parameters

Type	Parameters	Default
0: Fixed	None	
1: Mobile (uniform velocity)	VELOCITY HEADING	20 m/s, 45 deg
2: Mobile (uniform velocity, random heading)	VELOCITY	20 m/s
3: Mobile (random motion)	MAX_ RANDOM_ MOVEMENT	30 m

Table 4.3: Mobility parameters

energy required to operate (E_min) then that node will be assumed dead (not available for communication) until its energy exceeds E_min again later on in simulation (for EH nodes). Table 4.2 lists the parameters available for energy module which can be set differently for each node. The energy object keeps track of the energy available (for battery-operated or energy-harvested nodes) and total energy consumption.

4.2.3 Mobility Model

Our extended framework allows nodes to be mobile during simulation. Each node can be configured as fixed or mobile. The mobility module support three types of motion as summarized in Table 4.3 [85][86]. During simulation, each mobile node location is recomputed every second.

Type	Folder Name	Examples
Data files	/data	CSV files with energy consumption,etc.
Charts/plots	/charts	Line and/or bar charts of energy levels, etc.
Topology	/topology	Topology used before/after simulation
Logging	/logs	Simulation run and module level logging
Combined	/yyyy-mm-ddThh-mm-ss	All files generated during a specific run

Table 4.4: File management

4.2.4 Plotting and Data collection

These modules allow for real-time plotting and data collection during and after simulation for interactive analysis and comparison with useful information. The modules implements generic helper methods and utilize the python Matplotlib package [87]. The simulation script is responsible for utilizing these methods to plot/chart and collect/log appropriate information as required by the simulated algorithm and application scenario. The output files are managed by utilizing a separate folder for each type of files within the current working path (Table 4.4). Also for each simulation run, a separate folder, prefixed with the current date time is used for all files created during that simulation run. The output format includes CSV, PNG, and high-quality SVG and PDF which can directly be inserted into Latex and other publishing applications. HTML files are also created with embedded JavaScript for interactive plotting needed for presentation and on-line content. It utilizes the innovative charting library provided by Highsoft [88], which is free to use for personal and academic purposes.

4.2.5 Modified Node module

Enhanced framework requires a significant modification in the Node module. The Node object now contains node type, energy model object and mobility object. The modified send and receive methods check before transmission or reception whether the node has enough energy to perform the operation. Also the propagation model dictates whether a packet is received without errors (i.e. when the received signal power is greater than the threshold based on the distance between the sender and receiver nodes). The object also keeps track of the number of messages transmitted, received, or lost.

4.3 Simulation Example

In this section, we discuss a simulation example to highlight the features of the extended framework. We consider an Internet of Things (IoT) application scenario where an energy harvesting WSN (EHWSN) node is installed/embedded within the Thing (object that need to be monitored) [89][90]. Several of such objects with EHWSN nodes form a cluster (in virtual star topology) around a high-power coordinator node (or cluster head). EHWSN nodes can only communicate to their own coordinator (when they have enough energy). Coordinators are special wireless nodes which have sufficient power available and which can send data to the base station directly or via other coordinators (multi-hop) in a typical converge-cast application as illustrated in Fig. 4.2. These objects are mobile and can move around their neighborhoods or move to another neighborhood (within the range of a different coordinator). The coordinators are installed at strategic fixed locations throughout the facility.

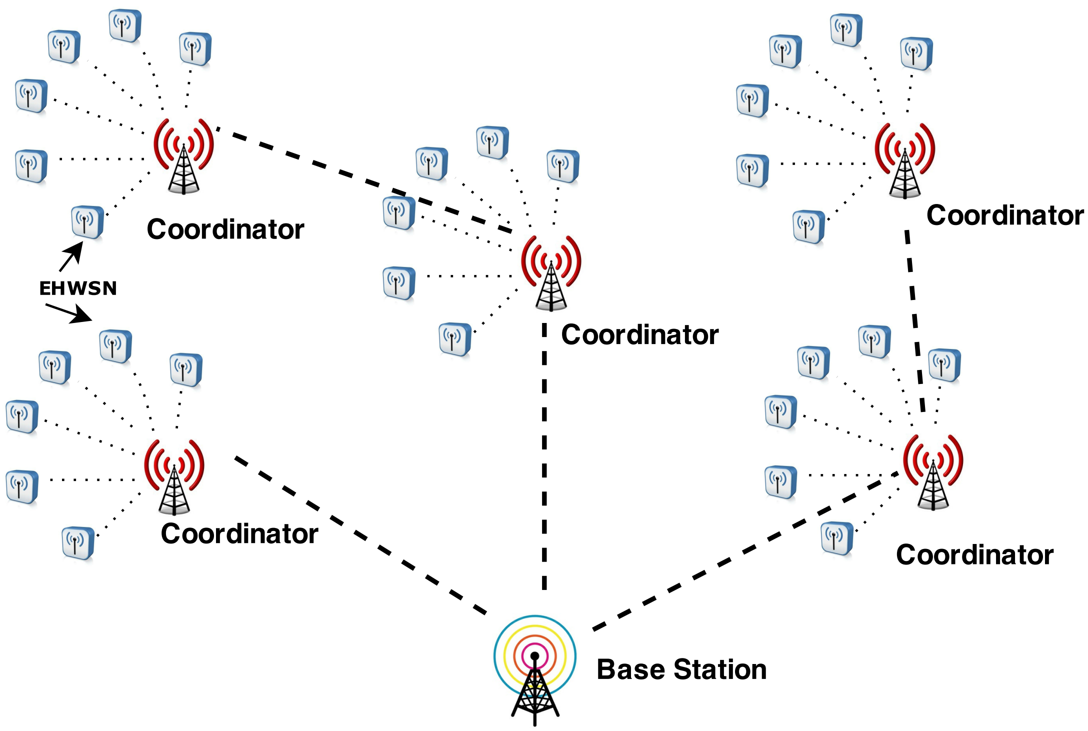


Figure 4.2: Proposed deployment scheme for EHWSN system

Figure 4.3 illustrates the scheme on a time scale and can be summarized as follows:

- The coordinator periodically (period = $T_c = t_4 - t_0$) broadcasts a beacon pulse with 10% duty cycle. The pulse contains the MAC address (48 or 64 bytes) of the radio, which is universally unique, and the number of registered nodes. After transmitting the beacon, it goes in the listening mode to receive messages from any EHWSN node which has any packets to send.

- The neighboring EHWSN nodes (which have enough power to operate) periodically wake up (period = $T_n > T_b$) with a certain duty cycle to receive the beacon pulse from the coordinator (t_1 in Figure 4.3). If the received coordinator's MAC address is different from the last communicated coordinator or the node has not communicated recently, then the node will send a registration message containing its MAC address and the power status (t_2 in Figure 4.3); otherwise the node will go back to sleep or send the data packet if any. The destination address will be set to the coordinator address so that any other neighboring nodes which are listening will ignore it.

- On receiving the node registration message, the coordinator record the registration information and increment the number of registered nodes (t_3 in Figure 4.3). If the coordinator receives a data message, then it will buffer it for future transmission to base station or for aggregation. The coordinator will acknowledge the received packet in both cases.

- The case of multiple child nodes transmitting in response to the same beacon pulse is also shown in Figure 4.3 during the second beacon period. The contention is avoided by using a random back off time before transmission. This will allow the node for wait for some random time before competing again for the channel. The winning node (which found the channel free and lock it for its communication) will transmit first (node A transmits at t_7 in Figure 4.3) and other nodes will wait for the channel to be free (e.g. node B transmits at t_9 in Figure 4.3).

4.3.1 Simulation setup

We only need to simulate the communication performance of one cluster formed by a coordinator and its children EHWSN nodes. The coordinator is placed in the middle of n randomly-deployed EHWSN nodes over a 600 m by 600 m area. We assumed that these nodes are constantly being charged during simulation and nodes are mobile (type=2, see

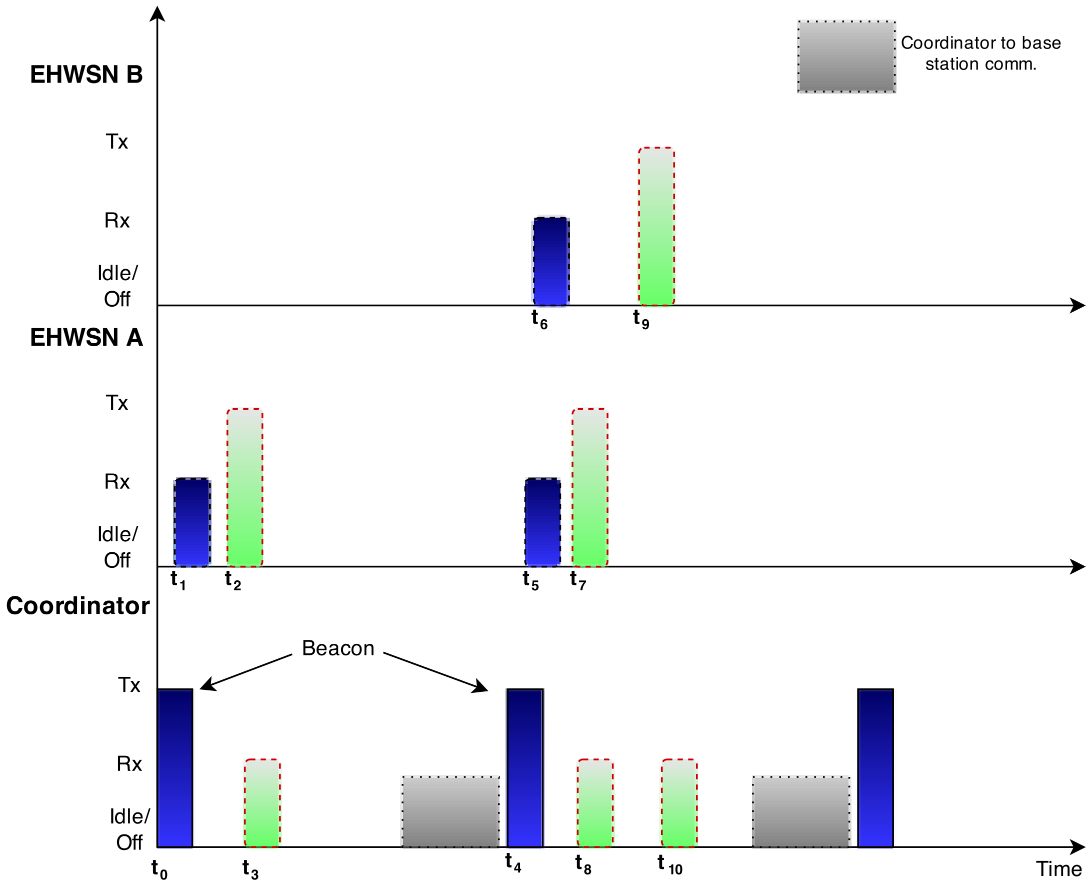


Figure 4.3: Timing diagram of coordinator's beaconing and node's transmission

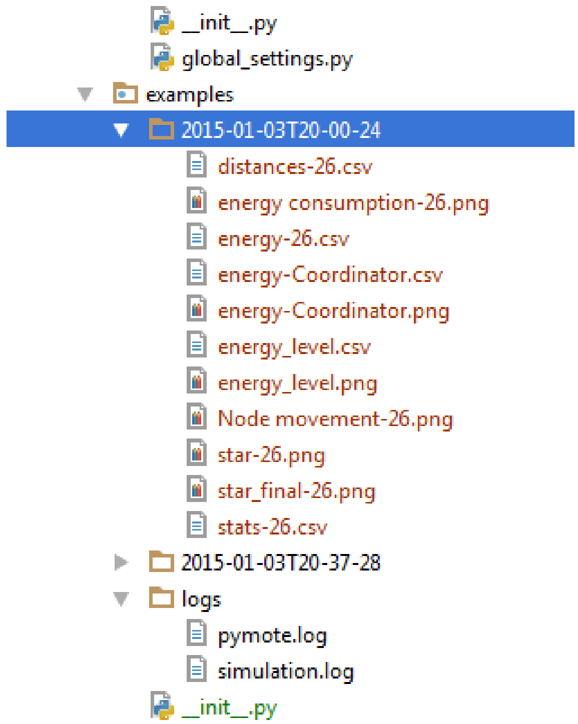


Figure 4.4: Simulation output files

Parameter	Name	Value
Tb	Beacon period	1 sec
b	Beacon duty-cycle	10%
n	No. of nodes	5 - 100
Sd	Data packet size	100 bytes

Table 4.5: Simulation parameters

Table 4.3). We consider beacon, registration and data packet sizes of 100 bytes (20 bytes of header followed by 78 bytes of payload and 2 bytes of checksum) while the acknowledgment packet size of 15 bytes (4 bytes of header followed by 9 bytes of payload and 2 bytes of checksum). We used default parameters for different modules as listed in Tables 4.1 - 4.3. Some other parameters are shown in Table 4.5. The simulation script utilizes the plotting and data collection modules to generate image and data files for easy visualization and analysis of simulation results (Figure 4.4).

4.3.2 Simulation Results

Figure 4.5 shows a simple topology generated for simulation using the Pymote. The center node (#1) acts as the coordinator for the EHWSN nodes (numbered 2 to 26). The node in lighter color means that its available energy is below E_MIN (=0.5 J). We arbitrarily selected node 5 and node 10 as borderline in terms of energy available (i.e. the initial energy at start of the simulation). Node 5 doesn't have enough energy to transmit in the beginning but charged up above E_MIN (Table 4.2) during the simulation and start communicating. On the other hand, Node 10 just has enough energy to send few messages before its energy level dropped below E_MIN. We set the charging rate to 0 for Node 10. The energy level change during the simulation run is shown in Figure 4.6.

Figure 4.7 shows the net node displacement during simulation as they move around with constant speed but in random directions. Figure 4.8 illustrates the energy consumption of all EHWSN nodes. We can notice that some nodes never communicated due to low energy (like nodes 2, 4, 11, 15, 20, 21 and 26) whereas nodes 5 and 10 were only active during some part of the simulation as we discussed earlier. Finally Figure 4.9 shows the location of nodes at the end of simulation.

Secondly, we increase the number of EHWSN nodes in the network from 10 to 100 in the increment of 5. The extended framework generates simulation output files for each iteration. The output files also include the overall summary. Figure 4.10 shows the generated topology for 100 EHWSN nodes (2 to 101). Figure 4.11 shows energy consumption plots for coordinator and other nodes combined (sum of energy consumption for all EHWSN nodes). The chart also shows number of messages (packets) received and

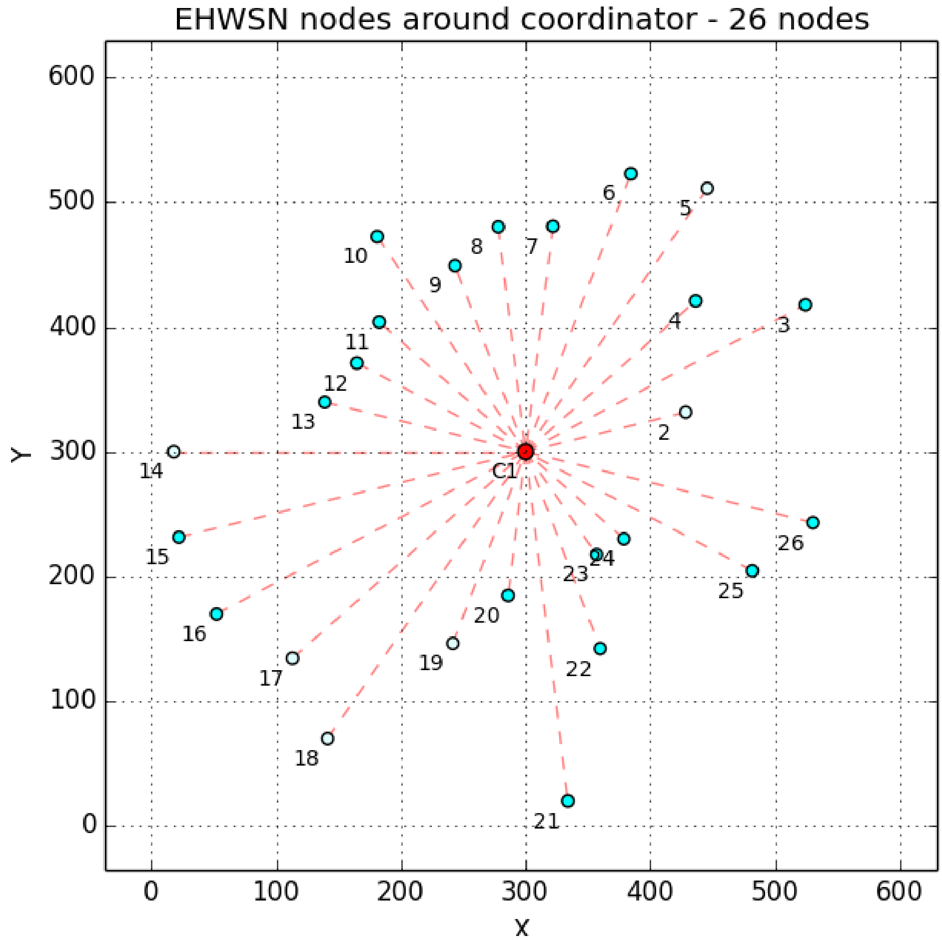


Figure 4.5: 25 EHWSN nodes around a coordinator

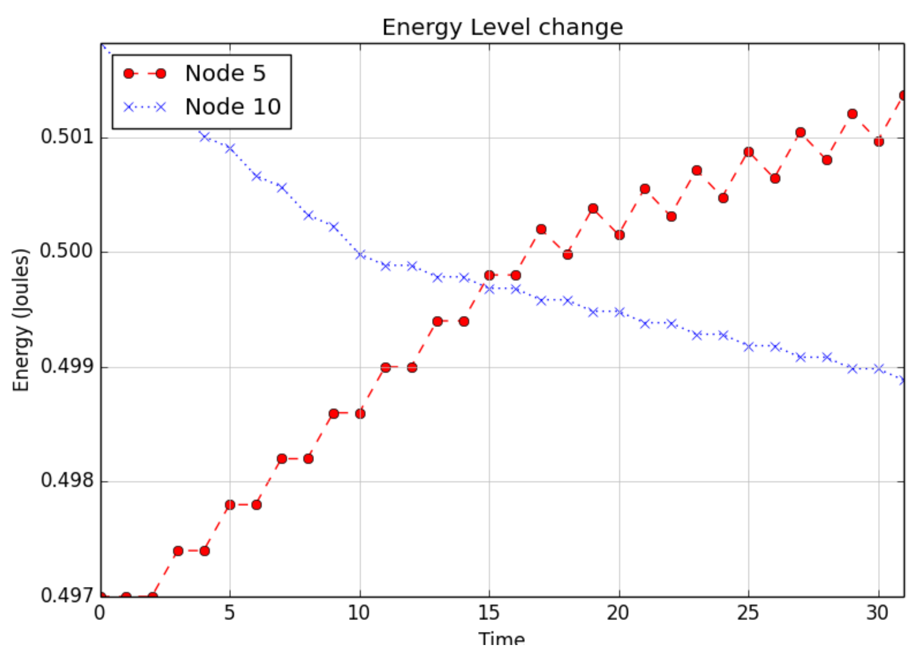


Figure 4.6: Energy level change for Node 5 and 10 with network size = 26

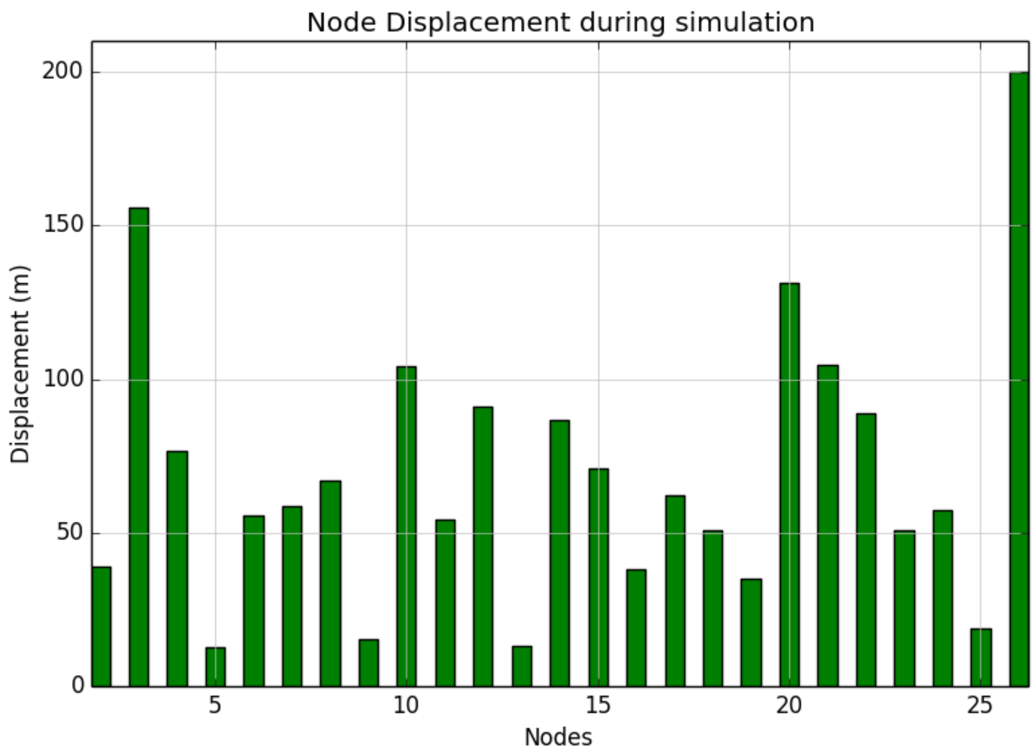


Figure 4.7: Node displacement during the simulation

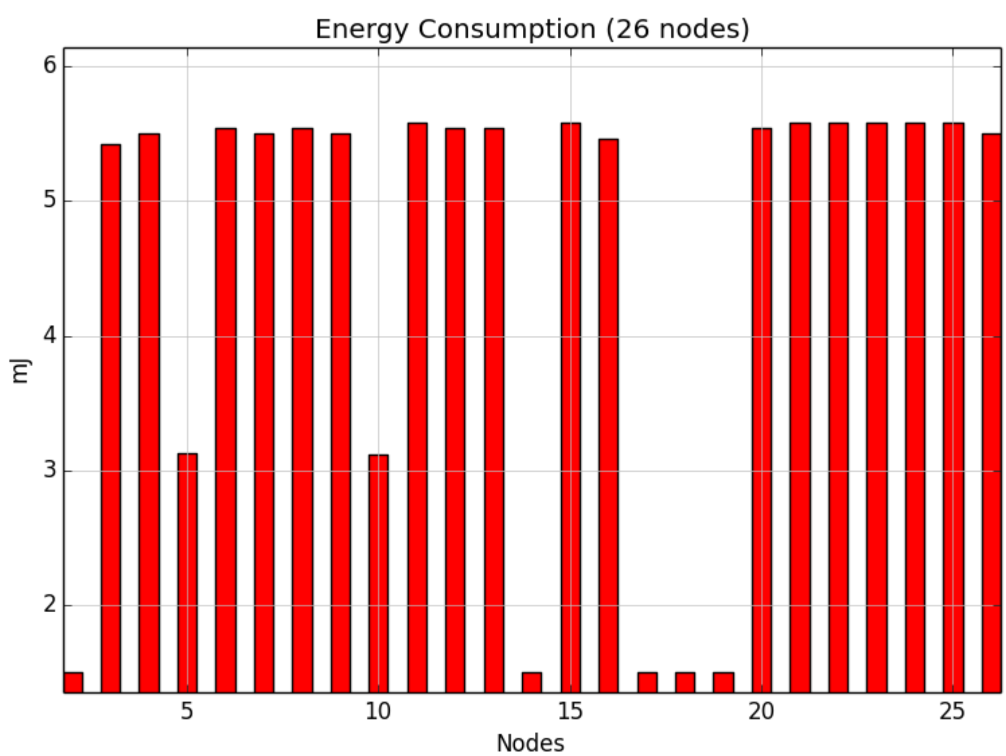


Figure 4.8: Energy consumption during the simulation

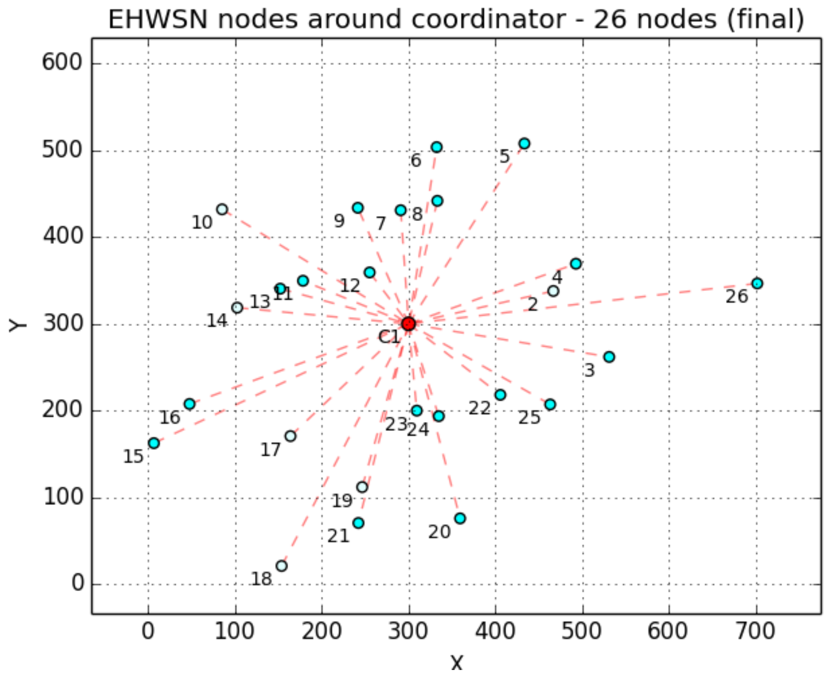


Figure 4.9: Final position of nodes at the end of simulation

lost at coordinator for each iteration.

Table 4.6 presented the overall simulation summary for all iterations. Node displacement and energy level change during the simulation for 100 nodes are shown in Figure 4.12 and Figure 4.13, respectively.

4.4 Conclusions

The development of a reliable and robust large-scale WSN system requires that the design concepts be checked and optimized before they are implemented and tested for a specific hardware platform. Simulation provides a cost effective and feasible method of examining the correctness and scalability of the system before deployment.

We utilized and extended the Python-based Pymote framework to allow packet level

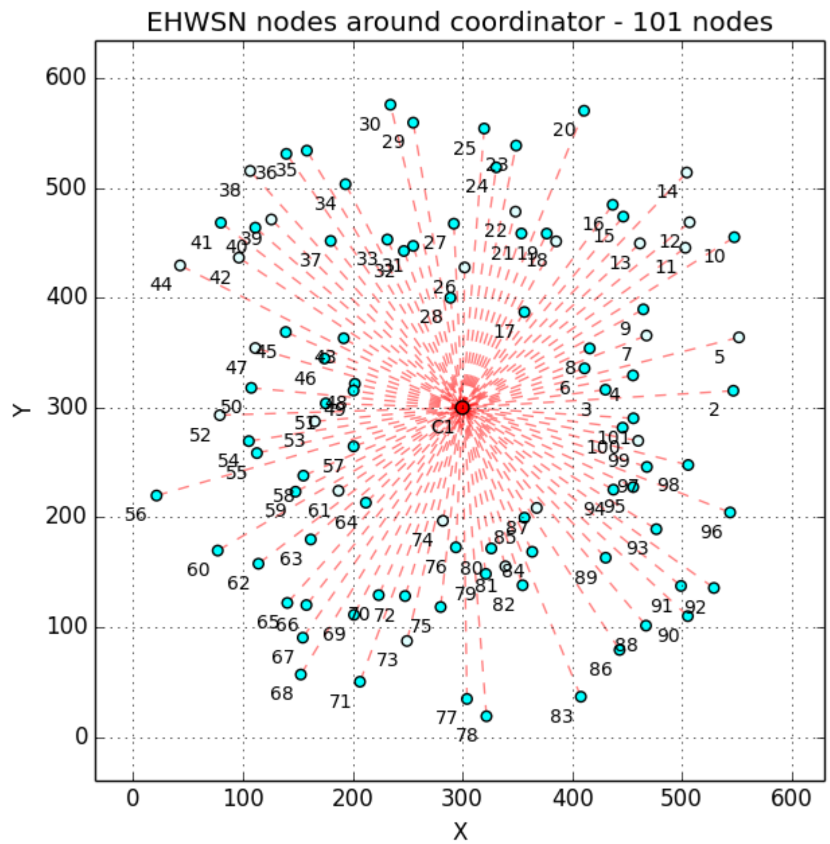


Figure 4.10: 100 EHWSN nodes around a coordinator

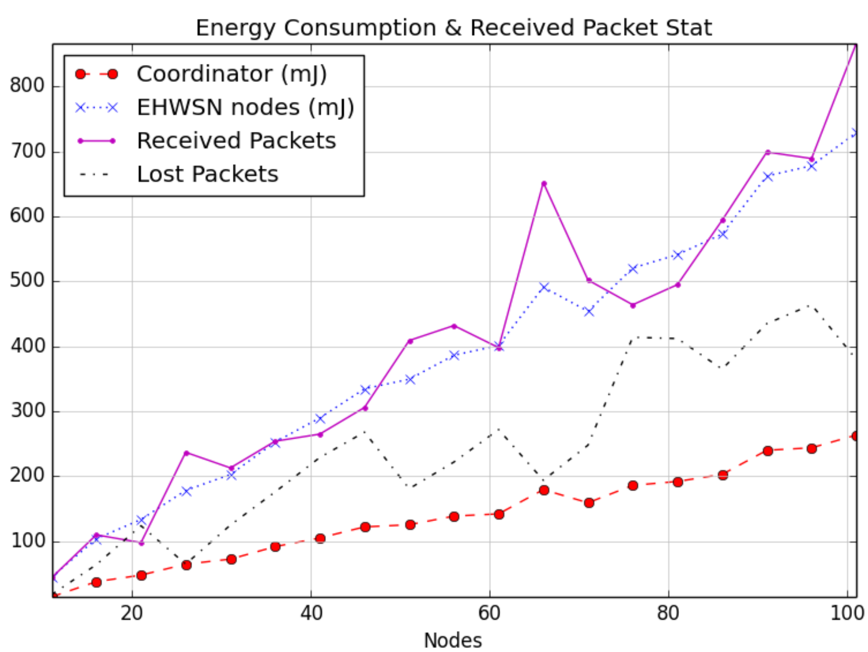


Figure 4.11: Overall summary

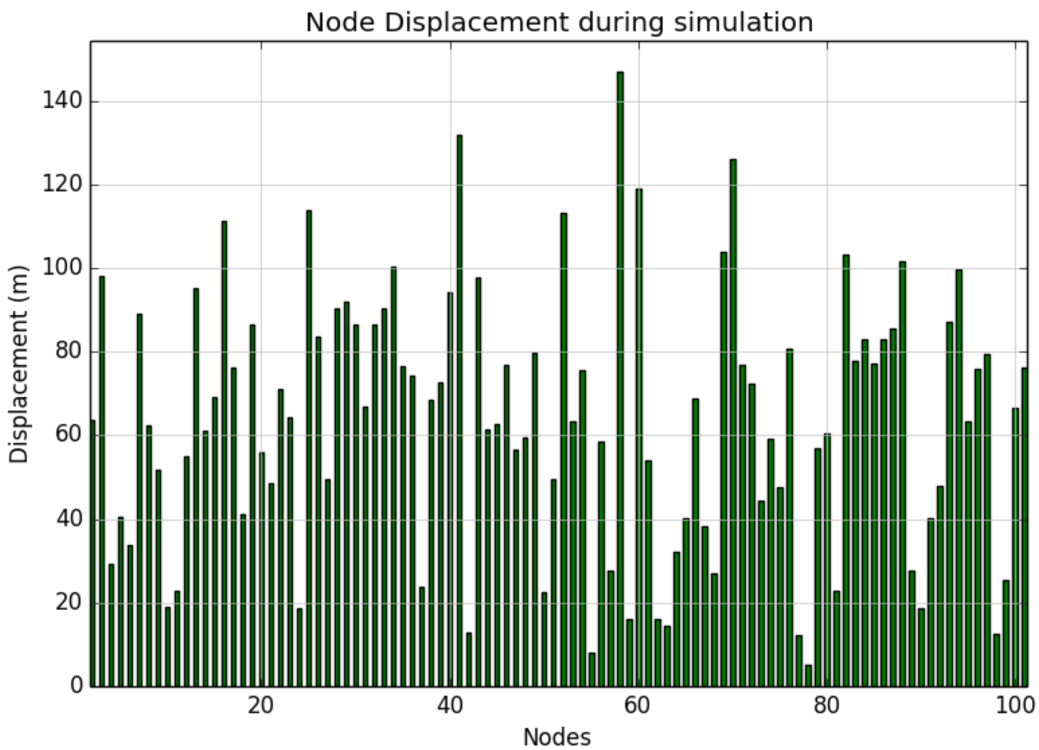


Figure 4.12: Node displacement during the simulation for 100 nodes

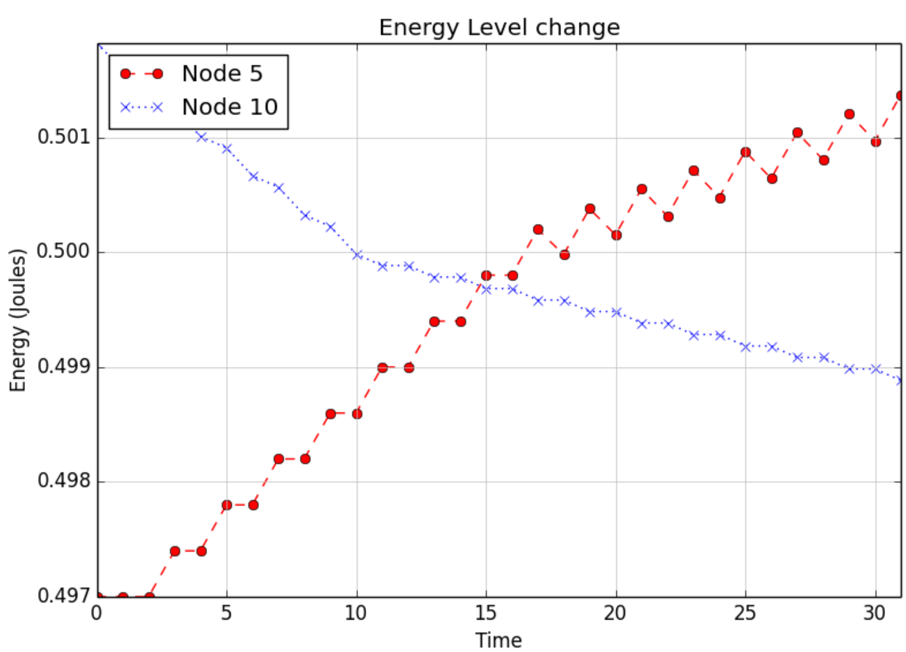


Figure 4.13: Energy level change for Node 5 and 10 with network size = 100

Nodes	Coordinator Energy consumption(mJ)	Total EHWSN consumption(mJ)	Received Packets at Coordinator	Lost Packets at Coordinator
11	15	45	44	18
16	38	104	110	64
21	48	134	98	124
26	65	178	237	65
31	73	203	213	125
36	92	253	254	176
41	105	290	265	229
46	122	335	306	268
51	126	349	409	181
56	139	386	432	222
61	142	401	398	272
66	180	491	652	194
71	159	454	502	248
76	186	521	464	414
81	192	541	495	412
86	203	573	594	365
91	240	662	699	435
96	244	678	689	464
101	264	729	866	380

Table 4.6: Simulation statistics

simulation at the physical layer. We implemented modules for propagation, energy consumption and mobility models. We also added graphing and data collection modules to enhance the Pymote base functionality and modified existing modules for node, network, algorithm and logging to support the extended framework. Finally, we performed a simulation example for a scheme to efficiently utilize EHWSN in an IoT application. The simulation results presented include topology maps, plots for available energy, bar charts for node displacement and energy consumption and comparison of received and lost packets at the coordinator node.

CHAPTER 5

DEVELOPMENT AND SIMULATION OF LOCALIZATION ALGORITHM

In a typical wireless sensor network (WSN), nodes are coupled to the physical world and have spatial relationship with other objects. In this context, localization in a WSN can be defined as the collection of techniques and mechanisms to measure the spatial relationship between nodes and physical objects. In other words, localization is the problem of determining the position of an object with respect to a reference frame or other object. The use of GPS receiver on each node (to have absolute coordinates) is unrealistic in a usual sensor deployment in terms of node's limited size/hardware and power.

Localization algorithms can be classified as range-based or range-free. The range-based technique utilizes either signal strength (RSSI), packet arrival time (TDoA), or the arrival angle (AoA) of signals to estimate distance between nodes. But these techniques require expensive measuring equipments. On the other hand, the range-free techniques utilize connectivity information such as position information from anchors and hop size to reach an anchor via multi-hop communication.

Since 2000, there have been significant efforts to develop an accurate and reliable range-free localization scheme. Most of the early work assumes isotropic topology or regular homogeneous node deployment and achieve acceptable performance for most application. However, real-world deployments are usually in irregular areas with few holes or structures which cause packets to be detoured [64]. In general, network anisotropy stems from various factors:

1. Concave deployment region,

2. Sparse and nonuniform sensor distribution,

3. Irregular radio propagation pattern, and

4. Anisotropic deployment terrain condition.

In this work, one of our main contributions is the development of a simulation framework for comprehensive study of network algorithms. We show its usability on localization algorithm simulation but it can easily be employed or extended to perform other wireless network-related simulation. Secondly, as part of this development, we introduce a generic topology generator with option and configuration to produce a specific topology for the intended simulation. The simulation example provides an in-depth statistical and visual analysis of the algorithm, which we believe should be followed as a guideline to perform systematic and comprehensive study of an algorithm and its simulation results.

Our other significant contribution is the development and simulation of enhanced DV-Hop for faster and accurate position estimation. We show that our proposed scheme is applicable to isotropic as well as anisotropic networks and provide a comparable or better solution when compared to other more advanced and complex range-free localization algorithms.

5.1 Network Model

This section describes the network model and the parameters used in this work.

N = Total number of nodes.

Na = Total number of anchors.

Nr = Total number of regular nodes = $N - Na$.

Ar = Anchor ratio, i.e. $\frac{Na}{N}$.

D = Average degree or connectivity (number of neighbors a node can communicate with directly).

R = Communication range or radius of each node (m).

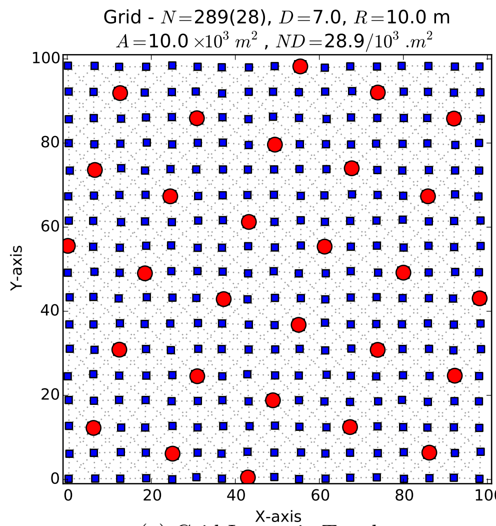
A = Active deployment area in $\times 10^3 m^2$ (dependent on the network shape).

N_D = Network Density i.e. nodes per $10^3.m^2 = \frac{N}{A}$.

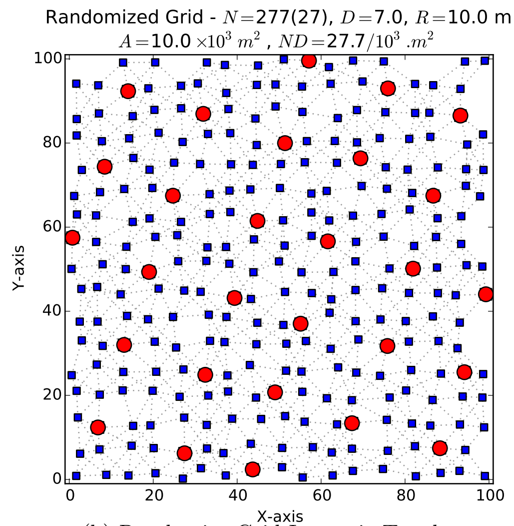
S = Isotropy or Network Shape.

For our study, wireless nodes are deployed in a two-dimensional (2D) square area. In case of anisotropic network, there are one or two rectangular structures or holes where nodes can't be deployed (or signal will not pass through these obstacles) and thus gives either O-, C-, S-, W-, T-, I-, H- or 8-shaped network as shown in Figures 5.1 and 5.3. The Number of nodes for each shaped network is dependent on the available deployment area (area of square - area of rectangular zones) to give us the same Network Density (N_D). All nodes are assumed to have the same transmission range (R). Each node is able to directly communicate with all its neighbors which are within the ring of radius R (dashed line between nodes in Figure 5.1 shows that these nodes can communicate directly). Anchors are equipped with GPS receiver and hence they are aware of their positions, while the other regular nodes are unlocalized. As shown in Figure 1, the anchor nodes are marked with bigger filled circle and the regular ones are marked with smaller square.

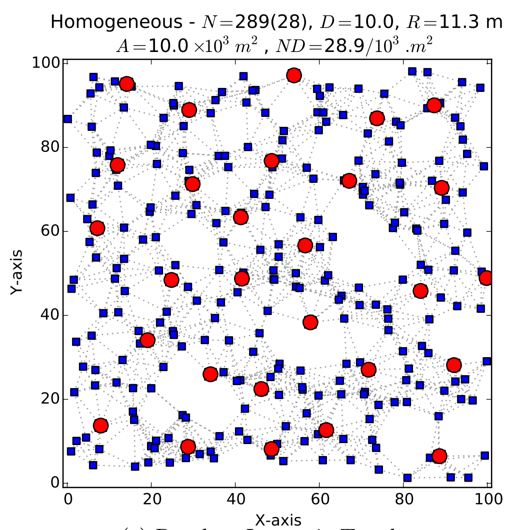
Networks are generated for simulation using topology generator algorithm with specified N, Na, A, S and D (or R). It is represented as a Graph with nodes as vertices and communication links as edges. In case of desired connectivity (D), the communication range (R) is adjusted accordingly. We also have the option to fix R and let the algorithm add or remove nodes randomly and iteratively to achieve the desired average network degree (D).



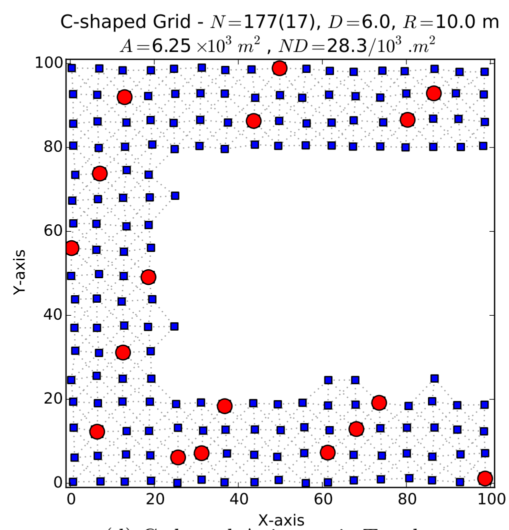
(a) Grid Isotropic Topology



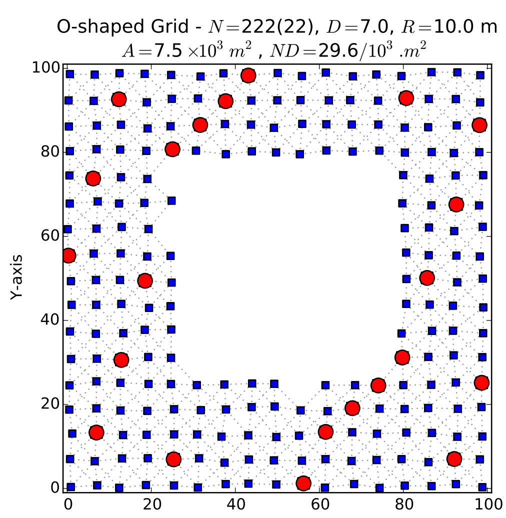
(b) Randomize Grid Isotropic Topology



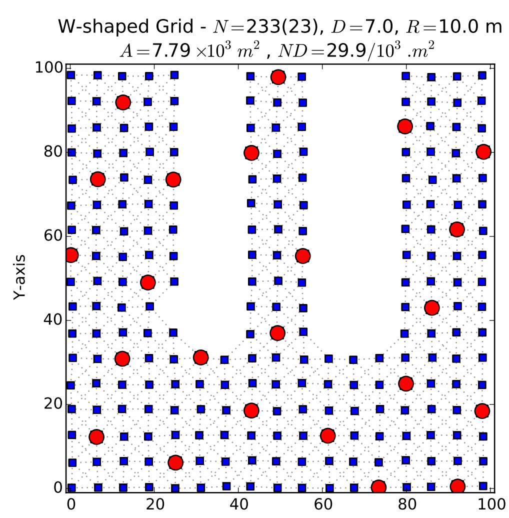
(c) Random Isotropic Topology



(d) C-shaped Anisotropic Topology

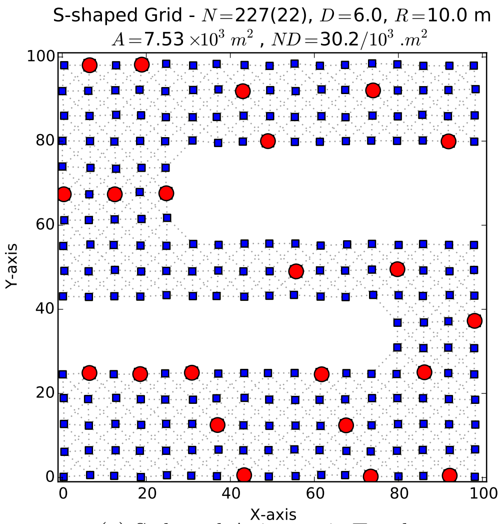


(e) O-shaped Anisotropic Topology

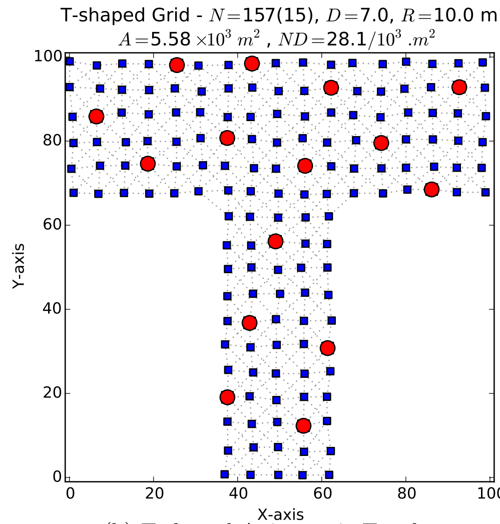


(f) W-shaped Anisotropic Topology

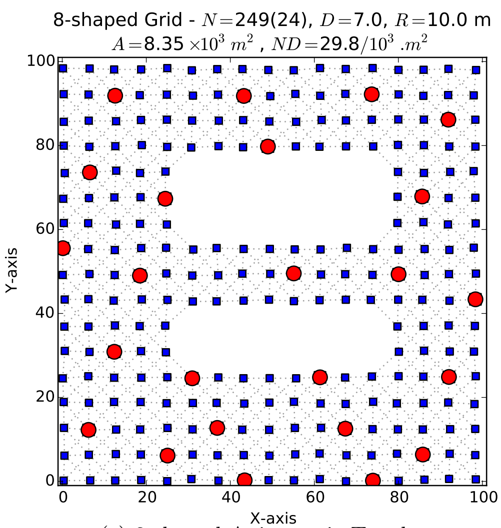
Figure 5.1: Network Topologies



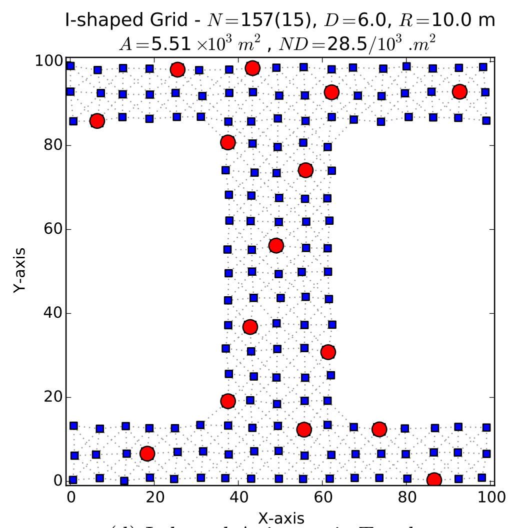
(a) S-shaped Anisotropic Topology



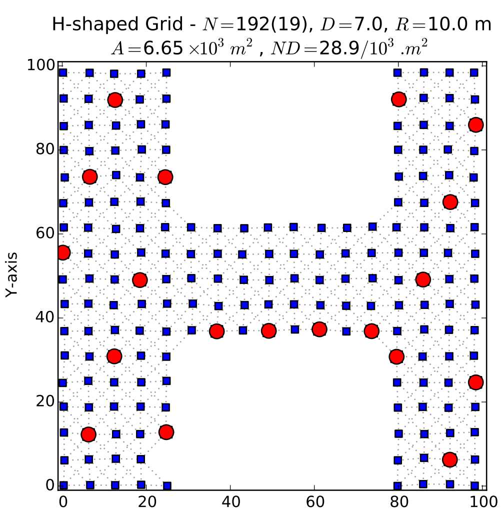
(b) T-shaped Anisotropic Topology



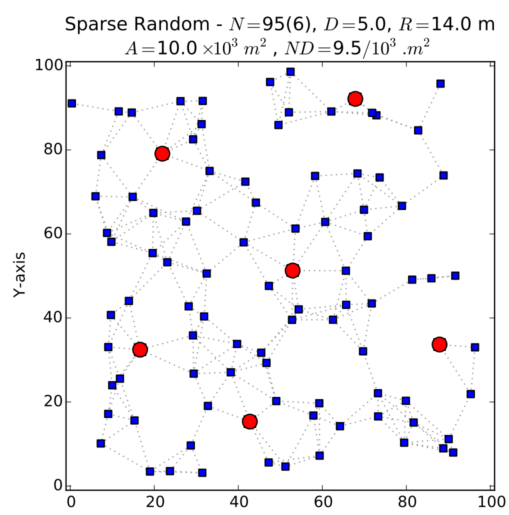
(c) 8-shaped Anisotropic Topology



(d) I-shaped Anisotropic Topology



(e) H-shaped Anisotropic Topology



(f) Sparse Random Anisotropic Topology

Figure 5.2: Network Topologies (continued)

5.2 Topology and Related Parameters

In isotropic networks, it is assumed that hop count distance between two nodes is proportional to their geometric distance (i.e. the path between the nodes has negligible detour). On the other hand, anisotropic networks are differentiated from isotropic networks in that they possess properties that vary according to the direction of measurement (due to detoured paths). Anisotropic characteristics result from various factors such as the geographic shape of the region (non-convex region), the different node densities, the irregular radio patterns, and the anisotropic terrain conditions [64][71][72]. In anisotropic networks, geometric distance between a pair of sensor nodes is not always proportional to their hop count distance, which undermines the assumption of many existing range-free localization algorithms. In the following section, we will evaluate both types of networks and analyze the performance of DV-Hop localization algorithm.

In our approach, we considered following five control parameters.

1. Network Density(N_D),
2. Average Degree(D) or Connectivity ,
3. Communication Range R,
4. Anchor Ratio(Ar),
5. Isotropy or network shape(S)
6. Degree of Radio Irregularity (DOI): The two nodes with distance d establish communication with the following probability [64]:

$$P(d) = \begin{cases} 1, & \dfrac{d}{R} < 1 \; - \; \text{DOI}, \\ \dfrac{1}{2\text{DOI}} \left(\dfrac{d}{R} - 1 \right) + \dfrac{1}{2}, & 1 - \text{DOI} \leq \dfrac{d}{R} \leq 1 + \text{DOI}, \\ 0, & \dfrac{d}{R} > 1 + \text{DOI}. \end{cases}$$

The first three parameters (N_D, D, R) are related in the sense that adjusting one will effect the other. For example, higher network density means more connectivity or increase in communication range will result in a better connected network. We can select a fixed value for one of these parameters and let the other vary to achieve the desired fixed value.

Figures 5.1 and 5.2 give some examples of the isotropic and anisotropic sensor networks. Anchor nodes are shown with a bigger circle and regular ones are shown with smaller square. The dotted lines shows the links (communication path if exists) between nodes . These or similar networks are used in our simulation. The title of each Topology in Figures 5.1 and 5.2 shows all the relevant parameters. For all networks, we have used the square area of 100 x 100 m^2, but the actual deployment area (A) depends on the node deployment shape. Figure 5.1a shows an isotropic sensor network where 289 sensor nodes (with an average degree (D) of about 7 which gives a radio range of approximately R=10 m) are uniformly distributed (uniform grid with some randomness) within the deployment area. The Ar is about 10% or Na = 28. Figure 5.1b shows an isotropic sensor network where 277 sensor nodes (with an average degree of about 7 which gives a radio range of approximately R=10 m) are uniformly distributed (uniform grid with 50% randomness) within the deployment area. The Ar is about 10% or Na = 22. Similarly the isotropic topology in Figure 5.1c with 289 nodes are randomly distributed with average degree of 10 and R=11.3m. All other topologies shown in Figure 5.1 are considered anisotropic due to irregular regions caused by holes or obstacles. Related parameters are shown on the title of each topology. Note that the different number of nodes is due to available area and therefore the network density is almost the same for all the topologies shown in 5.1 and 5.2, at around 29 nodes per 1000 m^2.

The following shows the Performance Matrix that is used in our approach.

1. Location estimation Error. It is the distance between the actual and the estimated node position:

$$err = \sqrt{(xactual - xestimate)^2 + (yactual - yestimate)^2}$$

2. Communication cost per Node/Anchor, in terms of number of packets transmitted and received during a simulation run,

3. Energy Consumption, which is proportional to the Communication cost and size of the packet.

4. Convergence time, this is the measure of the algorithm performance in terms of time taken to reach the best possible estimation.

5.3 Summary of DV-Hop

This section provides a brief summary of DV-Hop scheme [22].

1. First, anchors flood the entire network with their locations with hop-count initialized to one. The hop-count value is increased at every intermediate hop and each sensor records the minimum hop count as it receives it. Eventually, all nodes in the network will have information about the minimum number of hops to each anchor.

2. Each anchor computes the euclidean distances to other anchors and estimates the average hop length which is then broadcast to the neighbor nodes. The euclidean distance and the average hop length are calculated using the following formulas:

$$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{5.1}$$

   where d_{ij} is the euclidean distance between anchor i and j.

   The average hop length (hl_i) that anchor i computes, is given by the following formula:

$$hl_i = \frac{\sum\limits_{j \neq i} d_{ij}}{\sum\limits_{j \neq i} h_{ij}}, \tag{5.2}$$

   where h_{ij} is the shortest path hop count between anchor i and j.

3. At this stage, sensor k can estimate the shortest path length (L_{ki}) to anchor i by using the following formula:

$$L_{ki} = h_{ik} \times hl_n, \tag{5.3}$$

where h_{ik} is the shortest path hop count between anchor i and sensor k and hl_n represents the average hop length for the nearest anchor n.

4. By using the multilateration techniques, the estimated position $(x_k,\ y_k)$ of sensor k is obtained by the following minimization [23]:

$$(x_k, y_k) = \arg\min \sum_{i \in A} (L_{ki} - d_{ki})^2 \tag{5.4}$$

The close-form solution of Eq. 5.4 is provided in [22].

5.4 Simulation of DV-Hop

Simulation has always been very popular among network-related research. A large number of simulators have been proposed in the literature in which algorithms for mobile ad hoc networks (MANET) or wireless sensor networks (WSNs) can be implemented and studied. These simulators have different design goals and largely vary in the level of complexity and features. These simulators support different hardware and communication layers assumptions, focus on different distributed networks implementations and environments, and come with a different set of tools for modeling, analysis, and visualization.

As explained in chapter 4, we decided to use Pymote for our simulations, which is a high-level Python library for event-based simulation of distributed algorithms in wireless adhoc networks [84]. After one year of extension and development, the framework is completed and ready to perform interactive simulation [91]. We implemented graphing and data collection modules to enhance the Pymote base functionality and modified existing modules for node, network, algorithm, simulation and logging to support the extended framework. The extended framework utilizes the python Matplotlib package [87] and the innovative charting library provided by Highsoft [88], which is free to use for personal and academic purposes. The output format includes CSV, PNG, and high quality SVG and PDF which can directly be inserted into Latex and other publishing applications. HTML files are also created with embedded JavaScript for interactive plotting which is needed for presentations and on-line content.

5.4.1 Simulation Setup

We assume battery-operated fixed nodes with some initial energy which will dynamically adjust per node based on the number of transmission(Tx)/ reception(Rx), packet size, data rate, etc. We also record the number of transmitted and received packets for each node.

5.4.2 Statistics Logging and Plotting

During and after each simulation run, we collect and log several statistics which could be useful in the study and comparison of localization algorithms. We classify them in three categories, namely:

1. Node-level statistics, including number of Tx/Rx packets, power consumption of each node, signal to noise ratio (SNR) of each received packets.

2. Network-level statistics, such as total or average power consumption; average, max, min localization error, average transmission per node.

3. Simulation-level statistics, a simulation may consist of several runs and we log statistics for each run like simulation run time, keep separate arrays of above statistics for each run so that the final result can be analyzed or visualized.

We believe these statistics should be an integral part of any simulation study related to algorithm performance and hope this work provides a generic framework for simulation analysis related to WSN or MANET protocols and schemes. All the simulations intermediate and final results are stored in data files and appropriate images and interactive charts are saved in a separate folder. Most of the results presented in this section can be viewed interactively at the following site:

`http://www.ccse.kfupm.edu.sa/~gr199305420/dvhop`

5.4.3 Simulation Results

We simulated the DV-Hop algorithm on all topologies of Figs. 5.1 and 5.2. Table 5.1 summarizes the parameters for each topology used in the simulation. The results are summarized in Table 5.2. In this table, Runtime corresponds to the algorithm convergence time (total and per node). Localization error is given in terms of R (average and maximum). Localization error is low for all Isotropic topologies and acceptable for T- and 8-shaped networks. Whereas C-, W-, S-shaped networks shows higher average errors above R. Other statistics to compare is runtime or algorithm convergence time, number of packets transmitted and received per node, and the energy consumption per node. In Figure 5.3, the localization error for each node is shown with a line going away from regular node's real location, for some selected topology. This visually shows where and

Topology	Nodes	Anchors	Area $10^3 m^2$	Degree	Range
Grid	289	28	10	7	10
Randomized Grid	277	27	10	7	10
Random	289	28	10	10	11.3
O-shaped Grid	222	22	7.5	7	10
C-shaped Grid	177	17	6.25	6	10
W-shaped Grid*	233	23	7.79	7	10
S-shaped Grid	227	22	7.53	6	10
T-shaped Grid	157	15	5.58	7	10
8-shaped Grid	249	24	8.35	7	10
I-shaped Grid	157	15	5.51	6	10
H-shaped Grid	192	19	6.65	7	10
Sparse Random*	95	6	10	5	14

Table 5.1: Summary of Topologies for simulation

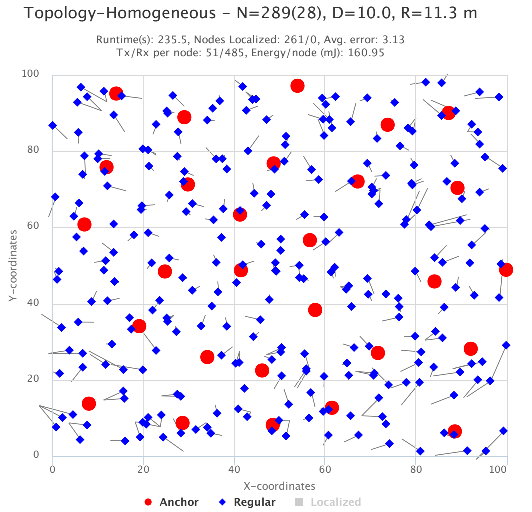
Topology	Runtime (per node)	Loc. Error (avg/max)	Tx/Rx	Energy
Grid	182 (0.63) sec.	0.14R/0.44R	55/376	121
Randomized Grid	179 (0.65) sec	0.25R/.81R	59/386	116
Random	235 (0.81) sec	0.28R/1.0R	51/486	161
O-shaped Grid	83.3 (0.375) sec	0.39R/1.5R	38/243	73
C-shaped Grid	60.22 (0.34) sec	1.4R/5.5R	28/174	52.5
W-shaped Grid*	94.2 (0.4) sec	1.4R/5.8R	37/239	72
S-shaped Grid	98.7 (0.34) sec	2.1R/6.9R	44/278	84
T-shaped Grid	35.2 (0.225) sec	0.36R/1.4R	22/143	43
8-shaped Grid	113.7 (0.45) sec	0.3R/1.3R	44/284	85.6
I-shaped Grid	34.4 (0.22) sec	0.66R/3.2R	22/140	42.24
H-shaped Grid	68.26 (0.36) sec	0.54R/2.5R	30/192	57.7
Sparse Random*	5.24 (0.06) sec	1.1R/2.7R	8/37	13.15

Table 5.2: Summary of simulation results for each topology

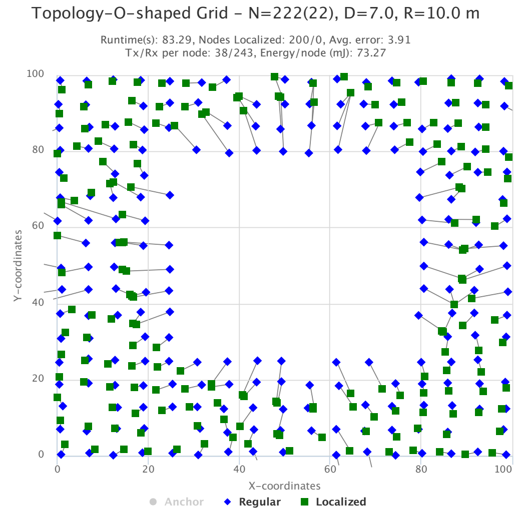
which nodes are localized accurately and which shows greater error. The reason for less accurate localization could be proximity to a hole or relative anchors position. Huge errors can be seen for S-shaped and W-shaped on edges while sparse network has high errors all around and four of the nodes are not even localized at around (80, 50).

Effect of Anchor ratio

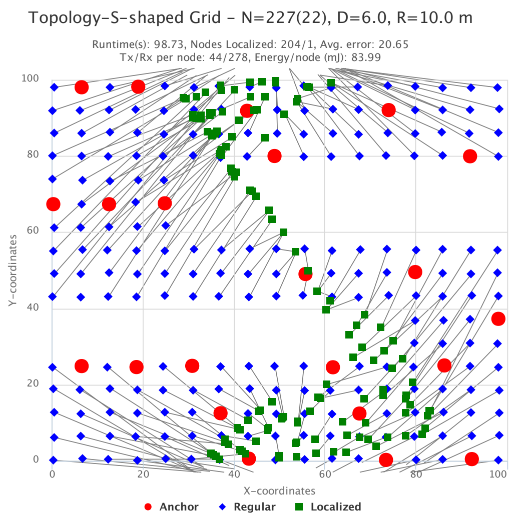
In this experiment, we vary anchor-to-regular-node ratio from 5% to 20% and study the effect on localization accuracy for each type of network. In Figure 5.4, the average and maximum localization errors are shown for Randomized grid, C-, and H-shaped network. We observe the optimal value to be around 10%. Also notice that the accuracy is pretty



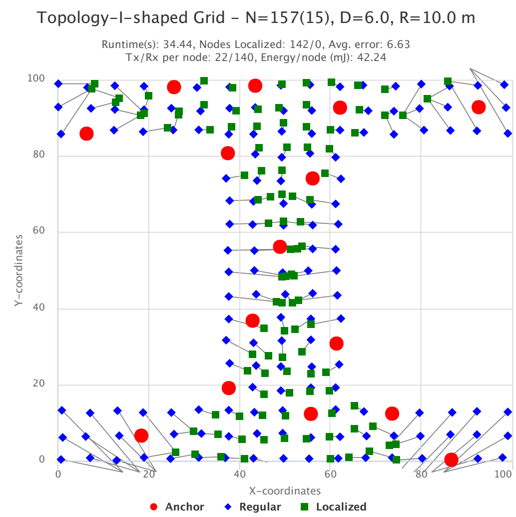
(a) Random network with relatively accurate estimation



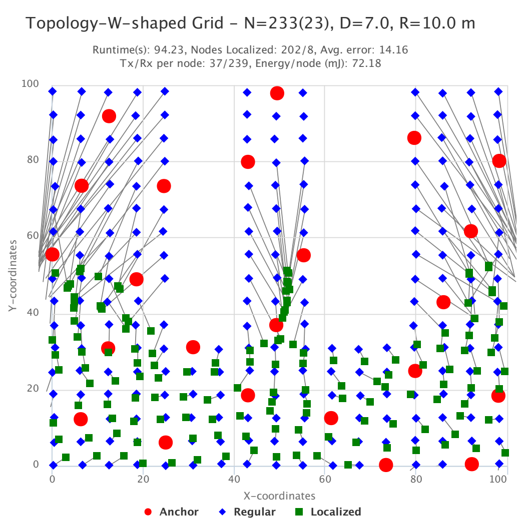
(b) O-shaped network with acceptable localization error



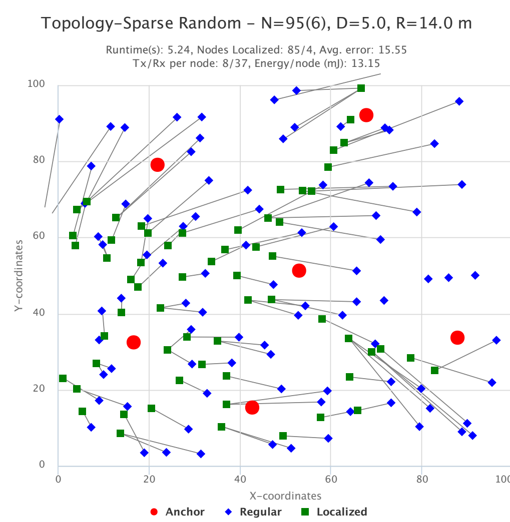
(c) S-shaped network with huge localization error



(d) I-shaped network with acceptable accuracy



(e) W-shaped network with large localization errors



(f) Sparse network with large localization errors

Figure 5.3: Six topologies showing localization errors.

much flat after 5% anchors (as long as they are uniformly distributed) since multilateration only requires minimum of three anchors. Higher anchor ratio just contribute to high communication/energy cost (Figure 5.5) and slow convergence as more anchors are flooding the network and in fact contributing in higher localization errors in some situations.

Effect of connectivity or communication range variation

In this experiment, we vary connectivity or degree (D) and study the effect on localization accuracy for each type of network. Since we don't want to change the number of nodes, the communication range (R) will vary with D accordingly. Figure 5.6 shows the average and maximum localization errors for Randomized grid, C-, and H-shaped networks. As can be seen from the plot, that degree doesn't play a significant role in localization accuracy. Higher degree means more paths between any pair of nodes. However, in DV-Hop, a node uses the shortest path from an anchor (in terms of hop count) for distance estimation and therefore higher connectivity may not always results in better accuracy.

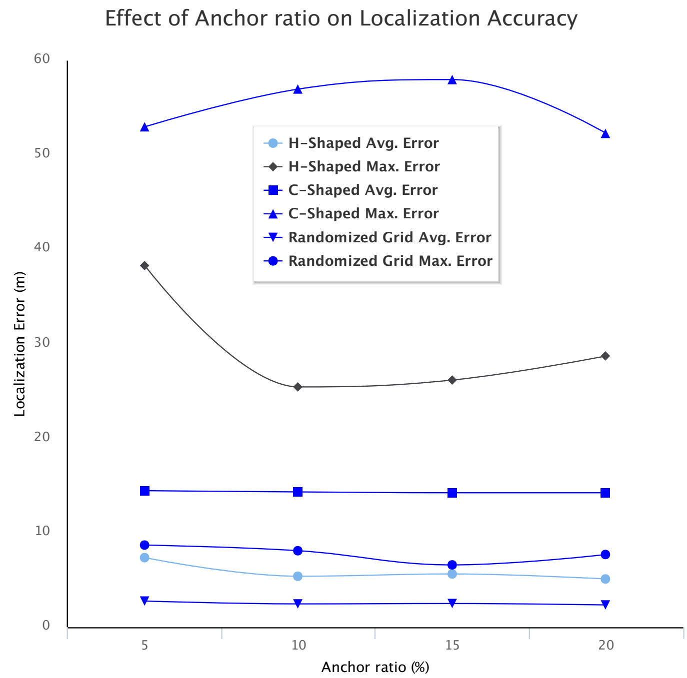


Figure 5.4: Effect of Anchor ratio on localization accuracy

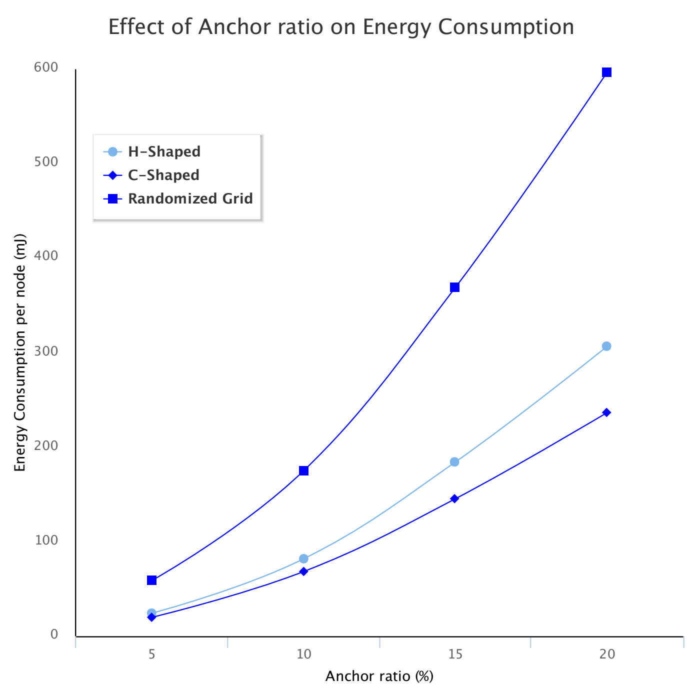


Figure 5.5: Effect of Anchor ratio on energy consumption

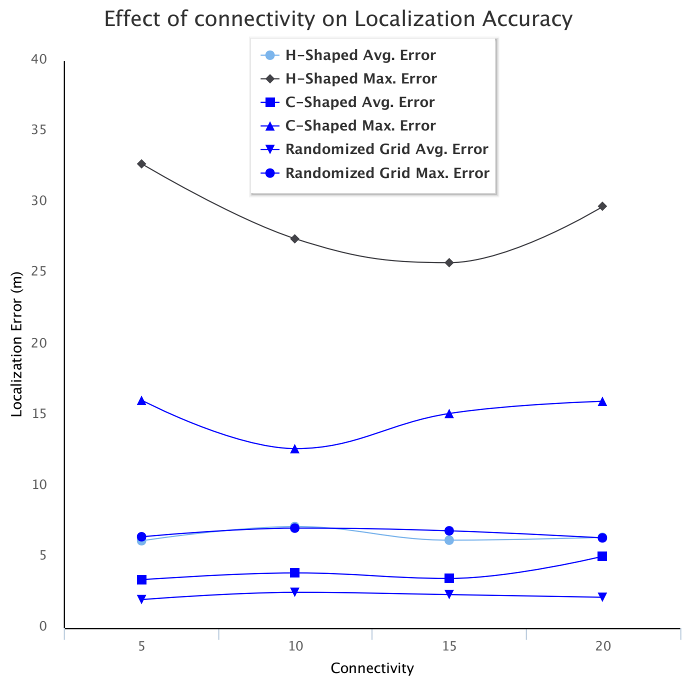


Figure 5.6: Effect of connectivity on localization accuracy

5.5 Proposed Scheme

During our extensive simulation of anchor-based, range-free localization algorithms for anisotropic networks, we observed that basically all recent range-free localization schemes [23][74][64][24] are trying to improve or extend DV-Hop or similar algorithms by ignoring distance estimation from certain anchors, which are not helping or are even distorting the accuracy of the distance estimation of a node. As explained in section 3.3, these algorithms achieve better accuracy for anisotropic networks at the expense of complex computational and communication overheads, which may not be feasible or desirable for low-power and low computationally resourced wireless sensor solutions like Internet of Things (IoT) applications. During our extensive simulation of all types of topologies, we discover that the we can achieve similar or better results by just introducing a control parameter in the first phase of the DV-Hop algorithm. We called this control parameter $MaxHop$. When a node receives the position of any anchor with hop-count, the algorithm ignores this information if the hop-count is greater than $MaxHop$, and the information is not propagated further. This results in faster and, in many cases, more accurate estimation in isotropic networks; while in anisotropic network, additionally, it bypasses anchors which will probably cause errors in estimation due to detoured paths and other anisotropic factors.

For our proposed scheme, the estimated position of sensor k can be obtained by using equations 5.3 and 5.4 :

$$
\begin{aligned}
(x_k, y_k) = \arg\min \sum_{i \in A} [(h_{ik} \times hl_n) - d_{ki}]^2 \\
\text{s.t. } h_{ik} \leq MaxHop
\end{aligned}
\tag{5.5}
$$

where A is a set of anchors $[1...N_a]$.

5.5.1 Determination of Best $MaxHop$

The value of $MaxHop$ is pre-selected based on the topology characteristics like Network Density (N_D), Anchor ratio (A_r), Isotropy or Network Shape and expected Degree of Radio Irregularity (DOI). We experimentally found that the value of $MaxHop$ in the range of 5 to 15, gives satisfactory results (i.e. average localization error under $0.3R$) for several topologies and anisotropic factors when anchors are uniformly distributed. This parameter can also be tweaked as needed for desired accuracy, power consumption and algorithm convergence rate. If it is desirable to find the best $MaxHop$ to achieve a certain accuracy or a desired algorithm convergence time then, Algorithm 1 and Algorithm 2 can be employed, respectively. Both algorithms try to find the best $MaxHop$ for the desired criteria iteratively. However, it is not guaranteed that these algorithms will always provide the optimal $MaxHop$, but the best result can be selected from the set of run after the iteration is completed.

In Algorithm 1, $MaxHop$ is set to a smaller number and is incremented after each simulation run. The algorithm will terminate when the desired accuracy is reached in terms of the average localization error ($AvgLocError$) or $MaxHop$ reached 15 (which means desired accuracy is not achieved for any value of $MaxHop$ from 5 to 15.

On the other hand, in Algorithm 2, $MaxHop$ is set to a higher number and is decremented after each simulation run. The algorithm will terminate when the desired convergence (run time) is reached or $MaxHop$ reached 5 (which means desired run time is not possible for any value of $MaxHop$ from 15 down to 5.

Algorithm 1: Finding best $maxHop$ for desired accuracy

```
Initialize maxHop to 5
do
    Run the DV-maxHop Algorithm
    compute AvgLocError
    if (AvgLocError<=DesiredAvgError)
        break
    else
        Increment maxHop
while (maxHop>=5 and maxHop<=15)
```

Algorithm 2: Finding best $maxHop$ for required convergence time

```
Initialize maxHop to 15
do
    Run the DV-maxHop algorithm
    compute AlgoRuntime
    if (AlgoRuntime<=DesiredRuntime)
        break
    else
        Decrement maxHop
while (maxHop>=5 and maxHop<=15)
```

5.5.2 Multi-objective Optimization

The applications that involve simultaneous optimization of several objective functions are called multi-objective optimization problems (MOPs). In such problems, the objectives to be optimized are normally in conflict with respect to each other, which means an improvement in one of the objectives will result in a degradation in one or more of the remaining objectives. There is no single ideal optimal solution, rather a set of good trade-off solutions known as Pareto-optimal, for MOPs to represent the best possible compromise among the objectives [92].

For simultaneously minimizing k objectives, a multi-objective optimization problem can be formulated as follows [93]:

$$\min \ y = f(x) = (f_1(x), f_2(x), \ldots, f_k(x))$$

where $x = (x_1, \ldots, x_n) \in X$ is an n-dimensional decision variable vector, and X is the decision variable space; and $y = (y_1, \ldots, y_n) \in Y$ where Y is the objective space. Each objective depends on the decision vector x.

A decision vector $x \in X$ is said to be Pareto-optimal with respect to X if there is no other decision vector that dominates x in X. The set of all Pareto-optimal solutions in the decision variable space is called as Pareto-optimal set. The corresponding set of objective vector is called as Pareto-optimal front.

Multi-objective Optimization Solution

A user usually needs only a limited amount of well distributed solutions along the Pareto optimal front. There are several techniques to find these relatively small amount of solutions.

Evolutionary algorithms (EA), which are a class of stochastic optimization methods based on population, are especially suitable and already popular for solving MOPs, because they can obtain a set of possible solutions in a single run. The multi-objective evolutionary algorithm (MOEA) strives to obtain an accurate and well distributed approximation of the true Pareto-optimal front that comprises the set of Pareto-optimal solutions.

Particle Swarm Optimization (PSO), which is inspired by the social behavior of bird flocking, is a population-based stochastic optimization method proposed by Eberhart and Kennedy [94]. PSO is simple in concept, easy to implement, and computationally efficient when compared with the other heuristic techniques, such as genetic algorithm. Researchers have extended the use of PSO from single-objective optimization problems

(SOPs) to MOPs. PSO has been reported to be very efficient in solving the MOPs as well, and several multi-objective particle swarm optimization algorithms have been recently proposed [93].

Multi-objective Localization Formulation

One of the research question for this work requires us to propose and develop a new localization scheme which can achieve multiple objective of accuracy and efficiency. Existing work in this area just focus on minimizing the localization errors. In this section, we formulate a multi-objective optimization to minimize the localization errors (or maximize the accuracy) and to minimize the convergence time (algorithm run time). The convergence time (and consequently the energy cost) minimization is achieved by reducing communication overhead. If we reduce the number of transmission during localization process, it will effectively reduce the overall energy consumption and will result in faster convergence. The two objective functions for the localization optimization are given below:

$$f_1(\mathbf{p}) = \frac{1}{N_r} \sum_{i \in N_r} \sqrt{(\hat{x}_i - x_i)^2 + (\hat{y}_i - y_i)^2} \tag{5.6}$$

$$f_2(\mathbf{p}) = \frac{1}{N} \sum_{i \in N} N_{Tx_i} \tag{5.7}$$

Where $(\hat{x}_i, \hat{y}_i)$ and (x_i, y_i) are the estimated and actual position of node i, respectively. N_{Tx_i} is number of packets transmitted by node i.

$\mathbf{p}$ is position vector of all nodes $= [\mathbf{u}|\mathbf{v}]$ where $\mathbf{u}$ and $\mathbf{v}$ are position of unlocalized nodes and anchor nodes (known), respectively.

The first objective function $f_1(\mathbf{p})$ is the average localization error and the second object function $f_2(\mathbf{p})$ is the average number of transmission per node. Both objective function are dependent on the position vector $\mathbf{p}$ of all nodes. The localization optimization can be formulated as:

$$\min \; y = f(\mathbf{p}) = (f_1(\mathbf{p}), f_2(\mathbf{p})) \tag{5.8}$$

As we mentioned, there is usually a set of good trade-off solutions known as Pareto-optimal for above minimization. Using our simulation framework, we provide a list of best possible solutions based on desired performance. We will show and discuss in section 5.5.8 that for our scheme, DV-maxHop, the two objectives are not always conflicting. We can find a Pareto-optimal solution which achieve accurate (small average error) as well as efficient (low communication/energy cost and faster convergence) localization in many scenarios.

5.5.3 Simulation Setup

We assume battery-operated fixed nodes with some initial energy which will dynamically adjust per node based on the number of transmission(Tx)/reception(Rx), packet size, data rate, etc. The Anchor ratio(A_r) is typically is set around 10-12% and communication range(R) is about 10m (unless otherwise noted). We also record the number of transmitted, received and lost packets for each node. During and after each simulation run, we collect and log several statistics which is quite useful in study and comparison of localization algorithms. They are either node-level statistics, network-level statistics or simulation-level statistics. We believe these statistics should be an integral part of any simulation study related to algorithm performance. All the simulation intermediate and final results are stored in data files (comma separated values or CSV format) and appropriate images (in PDF, SVG or PNG format) and interactive charts (JavaScript/HTML) are saved in a separate folder with date-time stamp. Most of the results presented in this section can be viewed interactively at the following site:

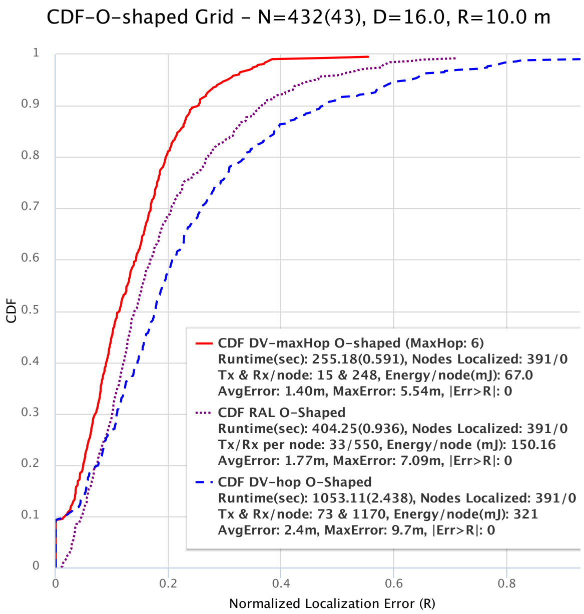
`http://www.ccse.kfupm.edu.sa/~gr199305420/dv-maxhop`

5.5.4 Simulation Results

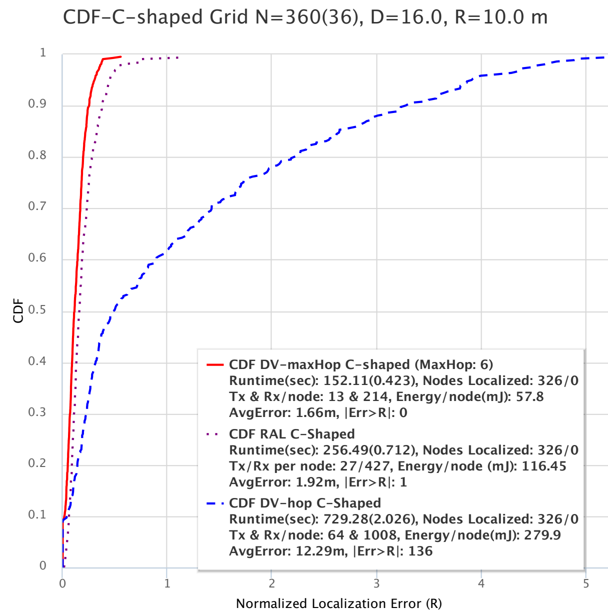
We simulated the DV-maxHop algorithm on all topologies of Figs. 5.1 and 5.2. We compare our proposed scheme with DV-Hop [22], RAL [23], AnSuper [24], SISR [73] and MDS-MAP [66]. DV-Hop is a benchmark algorithm while other algorithms claim to handle network anisotropy. We executed the simulation for an experiment several times and reported the average results. We observed that our scheme performs well in networks with wide range of degree (including low average connectivity, as low as 5 neighbors) and anchor ratio range of 5% to 25% as long as anchors are uniformly distributed in the network. Some of the recent algorithms require rather dense networks to provide acceptable localization accuracy.

We first compare the localization results of DV-maxHop with original DV-Hop and RAL, utilizing the cumulative distribution function (CDF) plots as shown in Fig. 5.7. These plots show the distribution of average localization errors in terms of R. The sharper rise in the beginning indicates that most errors are small. For example, in O-shaped network, 80% (CDF=0.8) of the nodes have average error under 0.2R for DV-maxHop algorithm (5.7a). For C- and S-shaped networks, RAL and our proposed DV-maxHop performs much better than DV-Hop with DV-maxHop is slightly better than RAL.

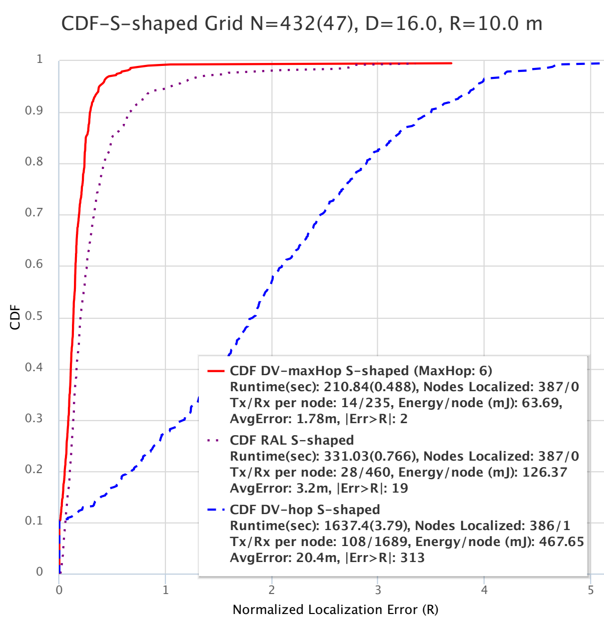
Next we evaluate the localization accuracy of DV-maxHop as compared to RAL for different topologies using the topological plots. Figs. 5.8 and 5.9 shows simulation results for O-, C- and S-shaped networks. The left plots are for RAL algorithm and the right ones are for DV-maxHop. The localization error for each node is shown with a line between the regular node's real location and the localized estimated location. The circles represent the anchors. This visually shows where and which nodes are localized accurately and which ones show greater error. DV-maxHop provides an accurate estimation well within 0.2R for all three topologies with much faster convergence resulting in lower energy and communication cost. We select $MaxHop$=6 for our proposed algorithm which give us optimal result in terms of accuracy and convergence. Higher value of $MaxHop$ (up to 10) will give us little better accuracy but much higher convergence time. Any value higher than 10 gives us greater errors, specially in S-shaped network, since distance estimates from farther anchors are inaccurate due to detoured paths. Higher values, in general, will also result in higher convergence time due to more messaging among the sensor nodes. In all cases the average error is smallest for DV-maxHop. In fact, in S-shaped network, only two nodes have errors above R and average is well within $0.2R$. Also, notice the huge accuracy (more than 10 times) for S-shaped network when compared to original DV-Hop and similar improvements in terms of runtime, power consumption and number



(a) O-shaped Anisotropic Topology

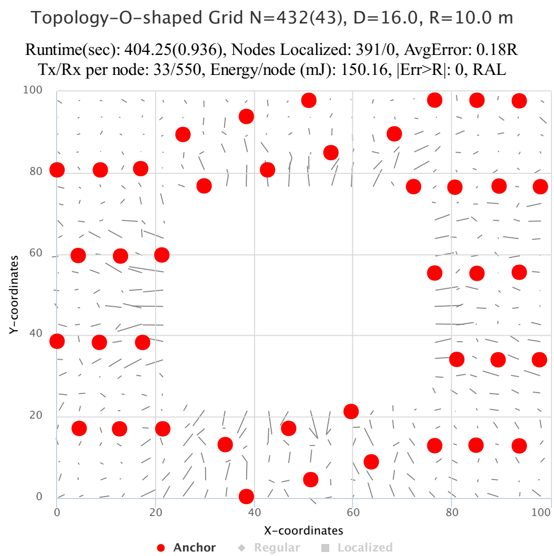


(b) C-shaped Anisotropic Topology

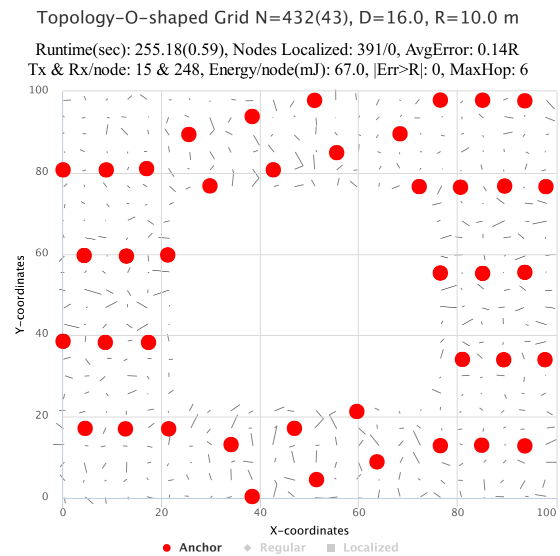


(c) S-shaped Anisotropic Topology

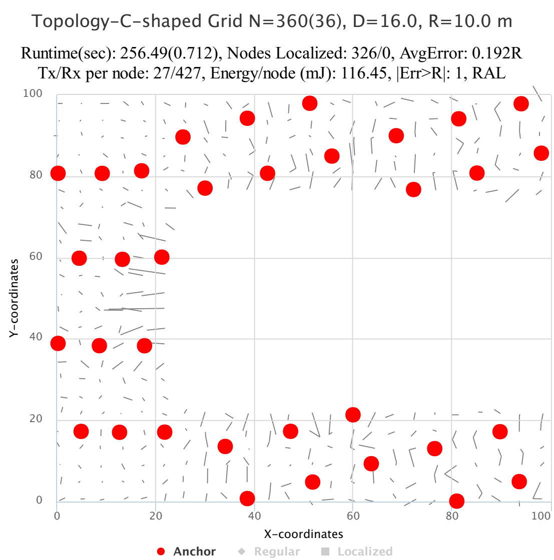
Figure 5.7: Cumulative distribution function (CDF) of O-, C- and S-shaped networks



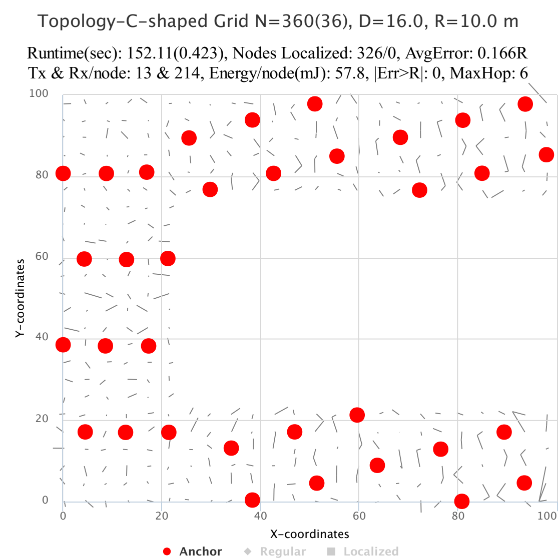
(a) RAL on O-shaped network



(b) DV-maxHop for O-shaped network

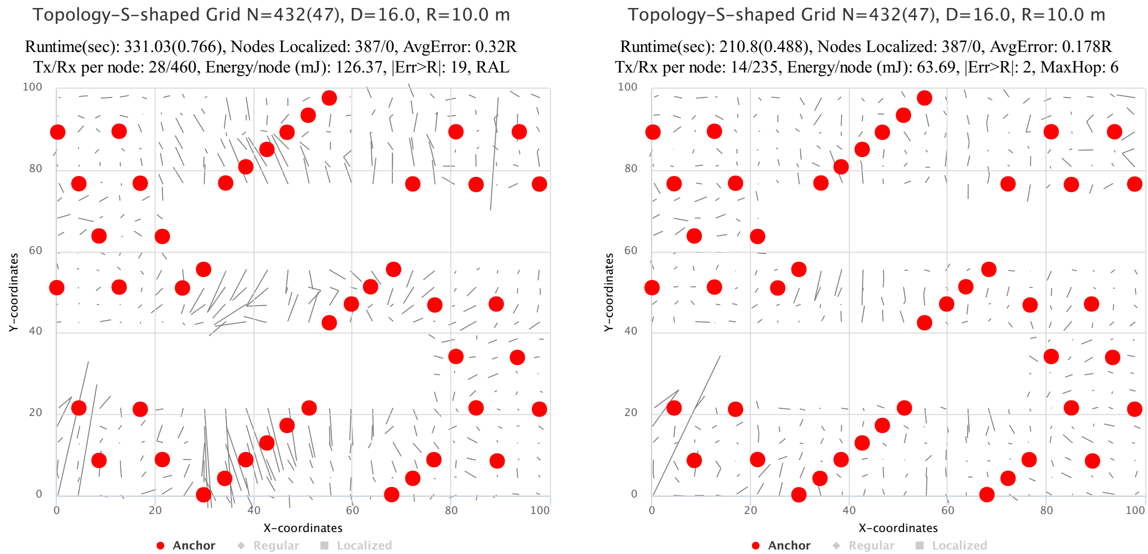


(c) RAL on C-shaped network



(d) DV-maxHop on C-shaped network

Figure 5.8: Localization Errors Comparison for O- and C-shaped networks.



(a) RAL on S-shaped network

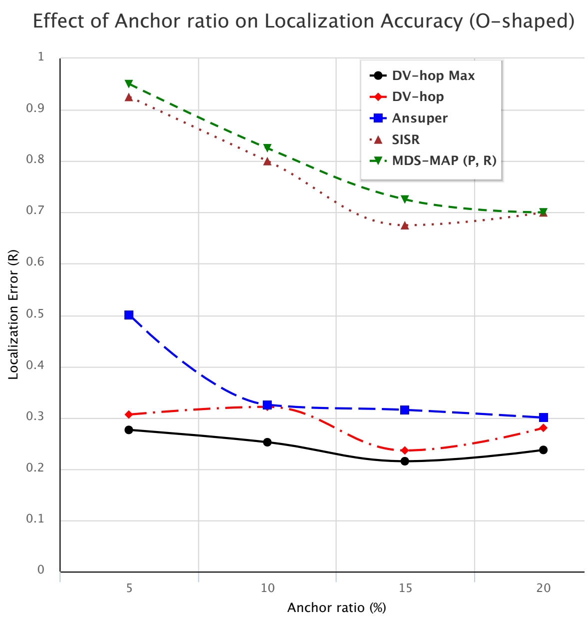
(b) DV-maxHop on S-shaped network

Figure 5.9: Localization Errors Comparison for S-shaped network.

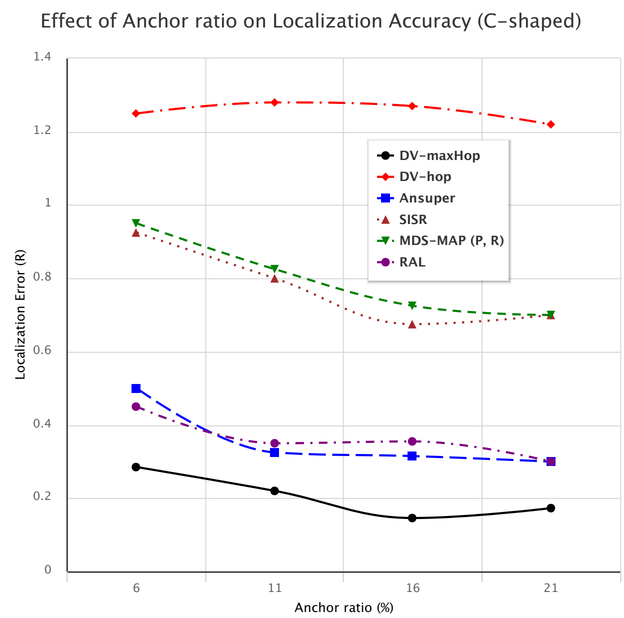
of transmission for all three topologies.

Effect of Anchor ratio

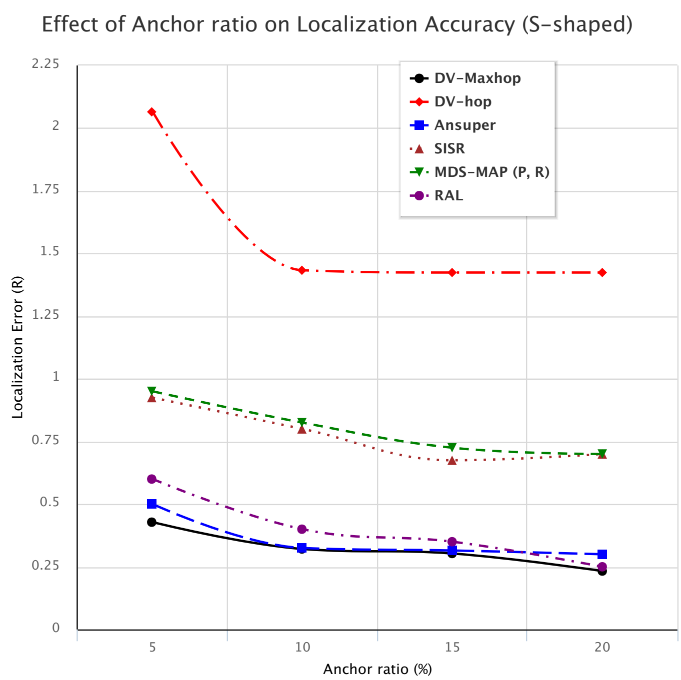
In this experiment, we vary the Anchor-to-regular-node (A_r) ratio from 5% to 20% and study its effect on localization accuracy for each type of network. In Figure 5.10, the average localization errors are shown for O-, C- and S-shaped networks. We observed the optimal value to be around 15%. Higher anchor ratio just contribute to high communication/energy cost and slow convergence as more anchors are flooding the network and in fact contributing in higher localization error in some situations. Our algorithm out performs all other algorithms as long as anchors are uniformly distributed within the whole network. We will discuss the requirement of uniform anchor distribution a later section.



(a) O-shaped Anisotropic Topology



(b) C-shaped Anisotropic Topology



(c) S-shaped Anisotropic Topology

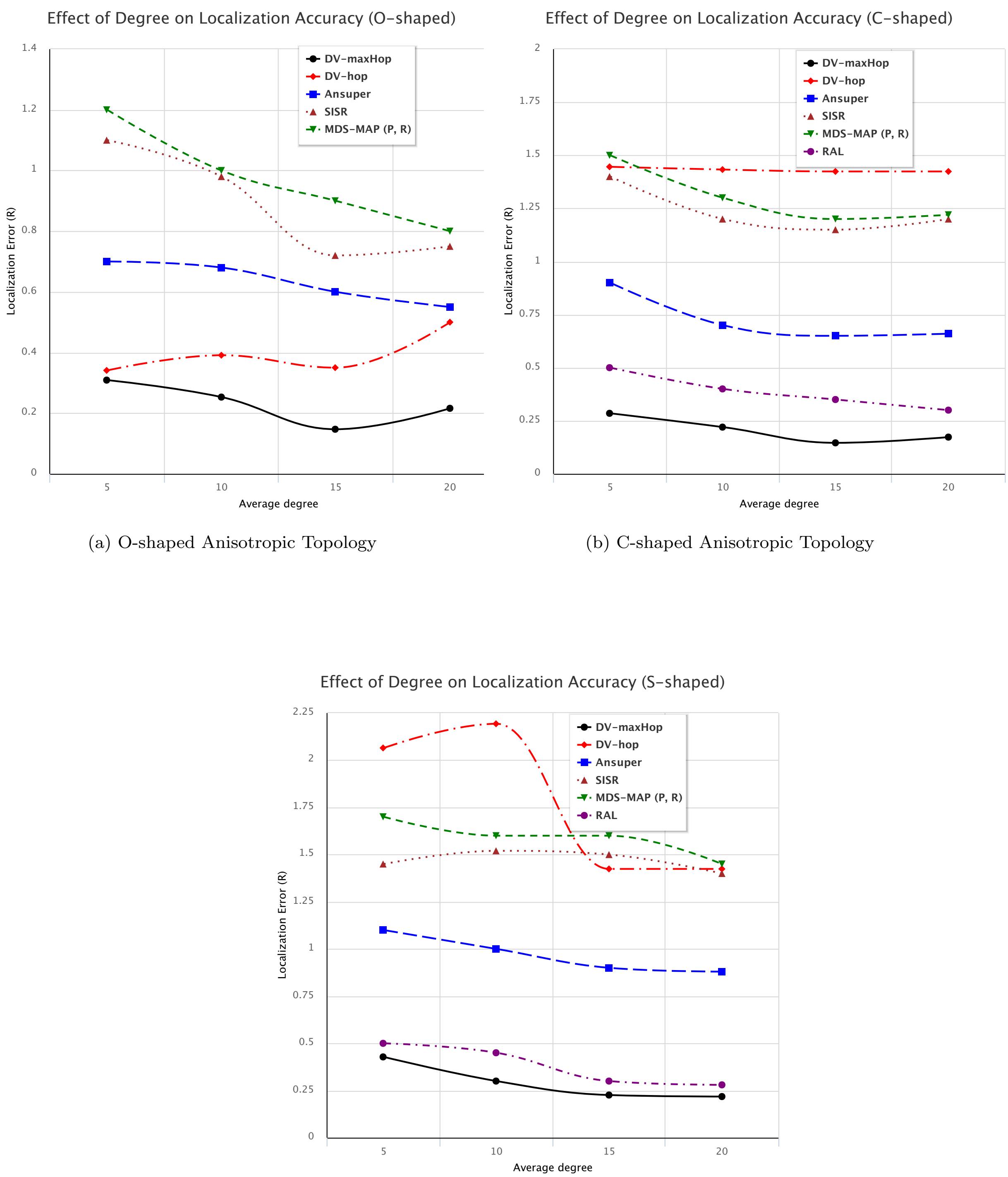
Figure 5.10: Effect of Anchor ratio on localization errors.

Effect of connectivity

In this experiment, we vary connectivity or degree (D) from 5 to 20 and study the effect on localization accuracy for each type of network. Since we don't want to change the communication range (R), the number of nodes (N) will vary with D accordingly. Fig. 5.11 shows the average localization errors for O-, C- and S- shaped networks for DV-maxHop, DV-Hop and some other algorithms. Our proposed scheme performs best with localization error around 0.2R for all networks for all the simulated values of degree. We noticed that the optimal performance is obtained for degree of around 15. Higher degree results in dense network which will not always contribute to better localization accuracy but definitely will converge slower due to high communication rate between nodes resulting in higher collision and large energy consumption.

Effect of DOI

In this experiment, we vary DOI from 0.1 to 0.6 and study the effect on localization accuracy for each type of network (Fig. 5.12). The DOI allows us to mimic radio signal propagation irregularities at the algorithm level. The higher values of DOI effectively make the network less connected and reliable estimation is highly dependent on the uniformity of the anchors. On a positive note, the localization algorithm in the less dense network will converge much faster due to fewer communication between the nodes. We sometime also notice better accuracy for higher DOI (specially for DV-Hop algorithm) due to the fact the lower connectivity may have avoided the reception of some of the distance information from farther anchors via detoured paths, which results in errors in



(a) O-shaped Anisotropic Topology

(b) C-shaped Anisotropic Topology

(c) S-shaped Anisotropic Topology

Figure 5.11: Effect of Degree/connectivity on localization errors.

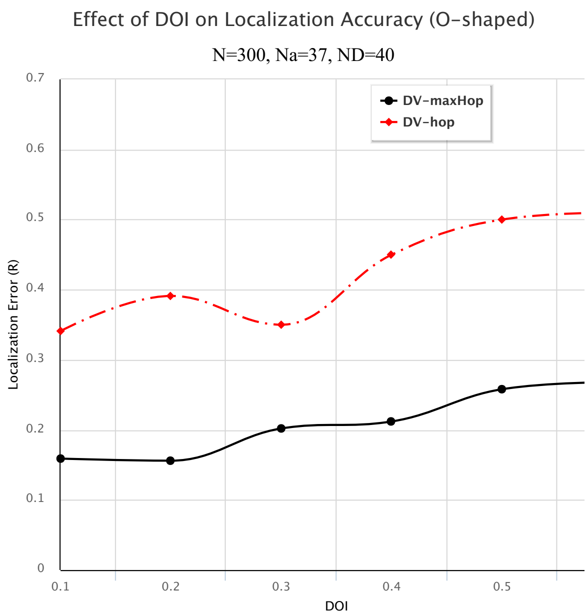
distance estimation.

Effect of $MaxHop$

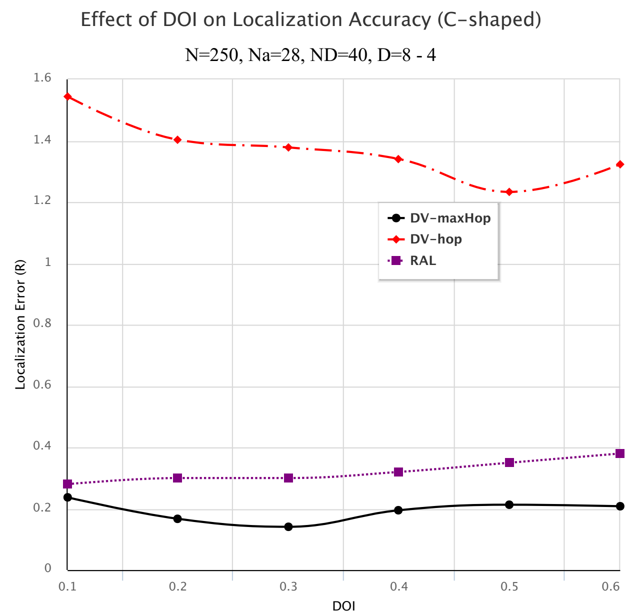
As we have shown earlier that our scheme outperforms the original DV-Hop algorithm in many respects, specially in convergence times (even for simple isotropic networks). Depending on the network topology and the selected value of $MaxHop$, our proposed algorithm can converge up to five times faster and results in similar savings in communication and energy cost than the DV-Hop. Fig. 5.13 shows the simulation output of randomized grid isotropic network for $MaxHop$=7 and 9. We achieved about 15% better accuracy (average error = 0.179R as compared to 0.21R) with lower $MaxHop$ quickly and with much lower communication and energy cost (these stats are shown in the subtitle on the top of each plot). Generally speaking, there is an optimal value which gives the best accuracy depending on the network characteristics. We will discuss this further in next subsection.

Sparse Networks

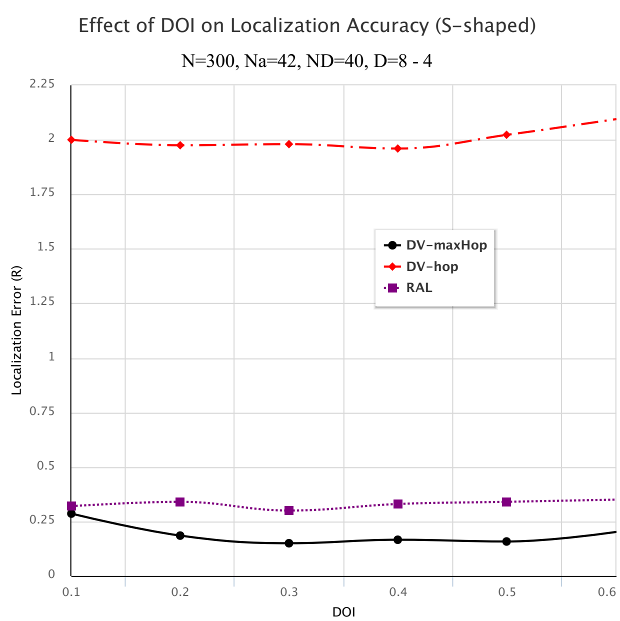
We also investigated the localization accuracy of our algorithm in sparse networks. In Fig. 5.14, the simulation outputs of DV-Hop and DV-maxHop are compared for a sparse network (having only 6 anchors) with average degree of only five with many nodes having only one or two neighbors (Fig. 5.2f). Again DV-maxHop is 50% more accurate than DV-Hop (average error = 0.5R as compared to 1.1R). Interestingly, DV-Hop converges little earlier in this situation probably because 4 of the nodes are not localized(unable to get distance estimates from at least 3 anchors) in DV-Hop simulation thus resulting in less



(a) O-shaped Anisotropic Topology

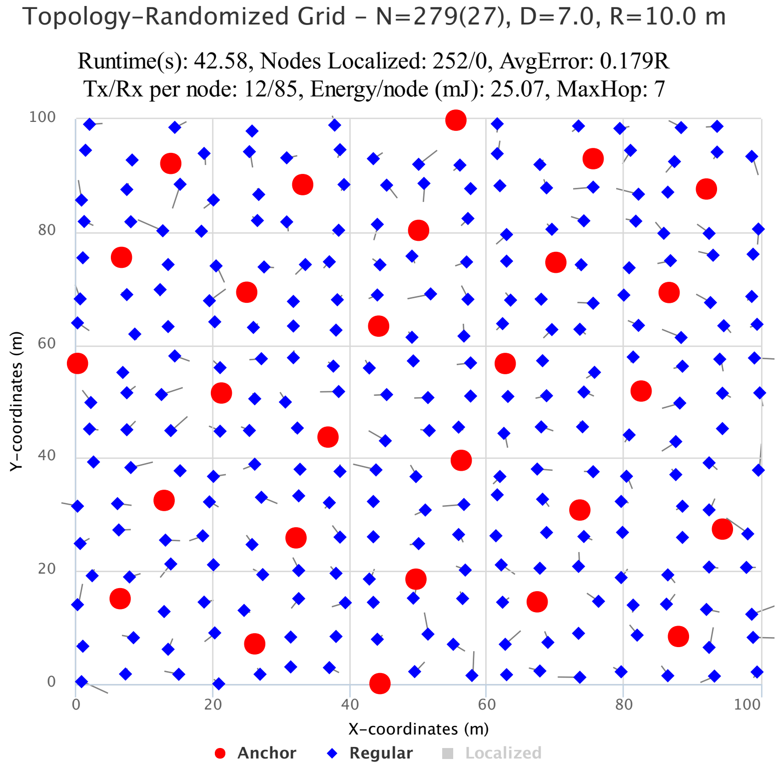


(b) C-shaped Anisotropic Topology

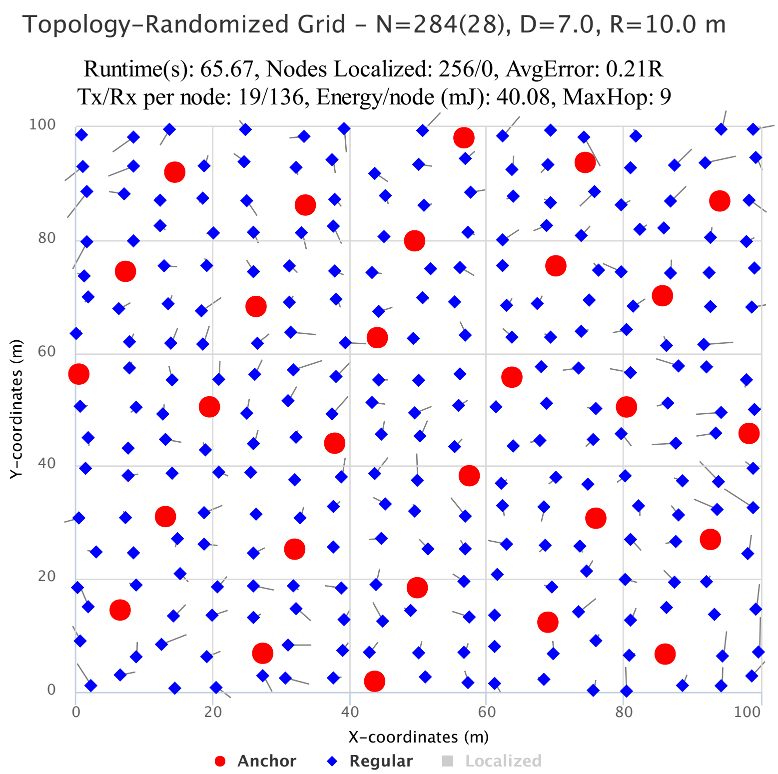


(c) S-shaped Anisotropic Topology

Figure 5.12: Effect of DOI on localization errors.



(a) Random network: simulation output for $MaxHop$=7



(b) Random network: simulation output for $MaxHop$=9

Figure 5.13: Effect of $MaxHop$ on localization errors.

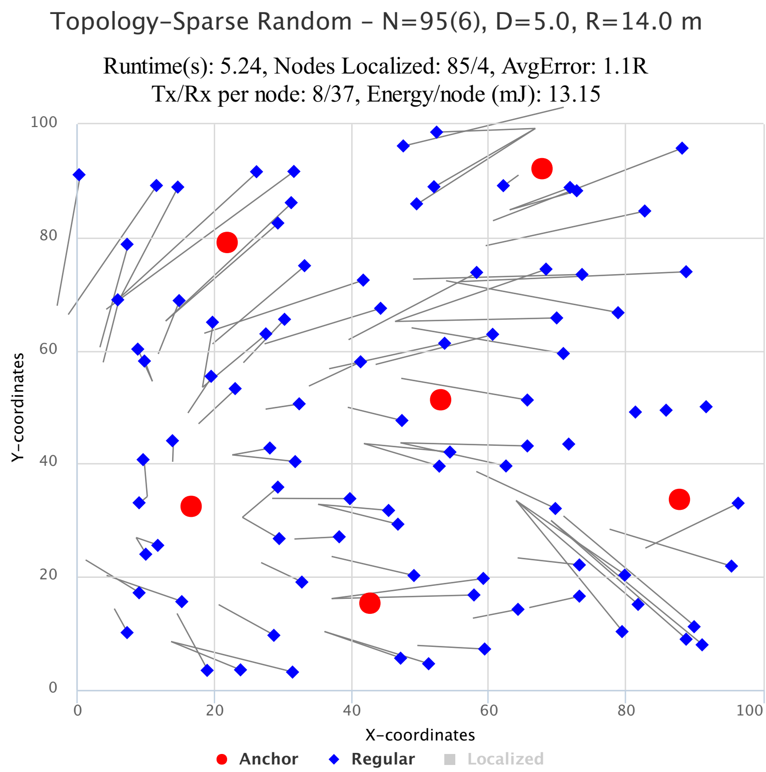
reception and broadcasting. Also notice that all nodes are localized in DV-maxHop simulation because anchors seem more uniformly distributed. We tried different values of $MaxHop$ ranging from 8 to 20. But the value of 12 gives us the optimal result in this network. Higher values make our algorithm effectively the same as DV-Hop (as there are only few anchors and estimates from farther anchors are probably less accurate due to communication between a node and the farther anchor in a curved path) and lower values result in lower accuracy as some good estimates will be ignored if hop distance is more than $MaxHop$.

5.5.5 Simulation Result Summary

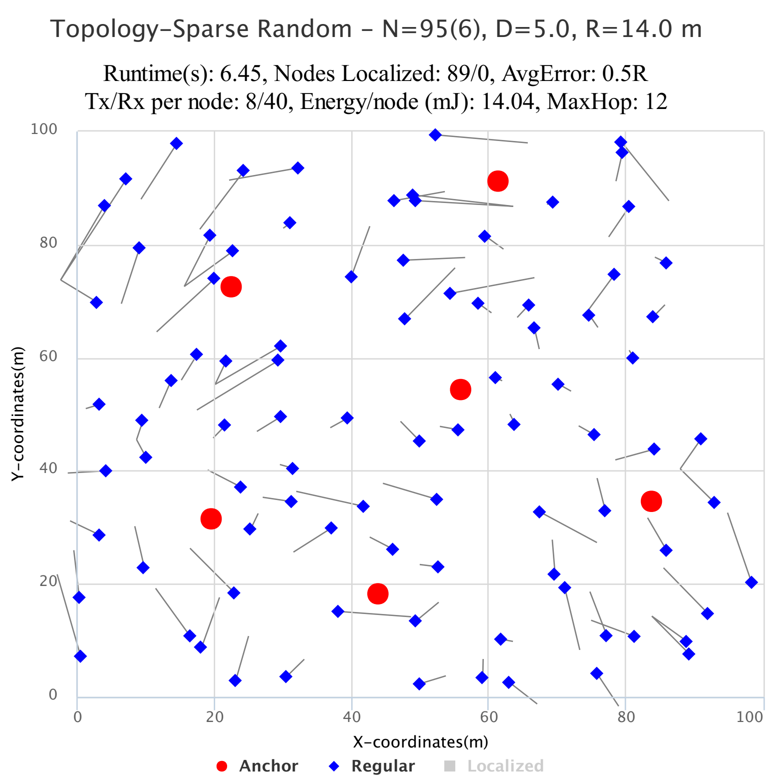
The table 5.3 shows the summary of simulation results of proposed scheme when compared with other algorithms. Overall our proposed scheme shows better results for all performance criterion. For O-shaped network, average localization error for DV-maxHop is about $0.14R$ with no errors above R and at the same time converges faster with half the energy and communication cost as compared to RAL. Similar results can be seen for C-shaped network. The accuracy and efficiency is even better for S-shaped network with average error is almost half of RAL ($0.18R$ vs. $0.32R$) with just 2 errors above R (vs. 19 for RAL).

5.5.6 Anchor Distribution Strategy

As discussed in the previous sections, anchor distribution can have significant effect on the accuracy and efficiency of any localization algorithms. Our scheme is no exception.



(a) Sparse network: simulation output for DV-Hop



(b) Sparse network: simulation output for DV-maxHop with $MaxHop$=12

Figure 5.14: Performance on a Sparse network

Topology (Algorithm)	**Runtime (per node)**	**Loc. Error (avg/max)**	**|Loc.Err < R|**	**Tx/Rx**	**Energy (mJ**
O-shaped Grid (DV-Hop)	1053 (2.44) sec	0.24R/0.97R	0	73 / 1170	321
O-shaped Grid (RAL)	404.25(0.936) sec	0.177R/0.7R	0	33/550	150
O-shaped Grid (DV-maxHop)	255.18(0.591) sec	0.14R/0.55R	0	15/248	67
C-shaped Grid (DV-Hop)	729.28(2.026) sec	1.2R/5.2R	136	64/1008	279.9
C-shaped Grid (RAL)	256.49(0.712) sec	0.19R/1.13R	1	27/427	116.5
C-shaped Grid (DV-maxHop)	152.11(0.423) sec	0.166R/0.87R	0	13/214	57.8
S-shaped Grid (DV-Hop)	1637.4(3.79) sec	2R/5.1R	313	108/1689	467
S-shaped Grid (RAL)	331.03(0.766) sec	0.32R/3.35R	19	28/460	126
S-shaped Grid (DV-maxHop)	210.84(0.488) sec	0.18R/3.7R	2	14/235	63.7
Sparse Random* (DV-hop)	5.24 (0.06) sec	1.1R/2.7R	> 10	8/37	13.15
Sparse Random (DV-maxHop)	6.45 (0.07) sec	0.5R/1.5R	3	8/40	14

Table 5.3: Summary of Simulation Results of Proposed Scheme

It is well known assumption for localization algorithm evaluation that anchors as well as other nodes are uniformly and randomly distributed [22][23][64][24]. It is intuitive that for anchor-based algorithm you need enough anchors at right places on the network. In this section, we will explore some of the ways we can distribute the anchors and compare the simulation results.

- **Random**: In this approach, anchors are deployed randomly. In most situation, it will not be optimal and significant localization errors are possible if some of the regular nodes are unable to get good distance estimation from at least three anchors. In fact, some nodes can remain unlocalized. This strategy might work fine in dense network or when anchor ratio is high.

- **Grid (every X node)**: In this anchor deployment scheme, anchors are placed in a grid uniformly covering the whole network. We start from one end of the network (say bottom left) and place near or choose Xth node as anchor. The value of X is function of anchor ratio (A_r). For example, for a 200 nodes network, if the desired $A_r = 10\%$, then X will be 20 (200/10) i.e. every 20th node will be an anchor. We used this scheme for most of our simulations so far. However, uniform anchor distribution is not guaranteed depending on the network shape, and uniformity of sensors distribution within the network.

- **Cluster Centroids**: In some deployments where nodes approximate locations are known or can be determined, we can utilize a clustering algorithm to find the optimal distribution of the anchors. The number of required cluster is determined by the desired anchor ratio (A_r). For localization problem, we can utilize the expectation-Maximization (EM) algorithm for 2-D Gaussian mixture distribution $D(\mathbf{p})$, which provides the classical clustering solution [95].

$$D(\mathbf{p}) = \sum_{k=1}^{K} \pi_k \mathcal{N}\left(\mathbf{p} \middle| \, \boldsymbol{\mu}_k, \boldsymbol{\Sigma}_k\right), \tag{5.9}$$

where K and π_k indicate the total number of clusters and the mixing coefficient of the kth cluster, respectively. $\mathcal{N}\left(\mathbf{p}|\boldsymbol{\mu}\right)$ is defined as follows,

$$\mathcal{N}\left(\mathbf{p}|\boldsymbol{\mu}, \boldsymbol{\Sigma}\right) = \frac{1}{(2\pi)\,|\boldsymbol{\Sigma}|^{1/2}} \exp\left\{-\frac{1}{2}\left(\mathbf{p}-\boldsymbol{\mu}\right)^{\mathrm{T}} \boldsymbol{\Sigma}^{-1}\left(\mathbf{p}-\boldsymbol{\mu}\right)\right\},$$

where $\mathbf{p}$ is the position vectors of all nodes. $\boldsymbol{\mu}_k$ is the position vector of centroid of cluster k and $\boldsymbol{\Sigma}_k$ is the 2×2 covariance matrix of the kth cluster.

At the first step, EM algorithm calculates each nodes value of degree of dependence that is referred to as responsibility. The responsibility shows how much a node depends on a cluster. The nth nodes value of degree of dependence on kth cluster is given by following equation.

$$\gamma_{nk} = \frac{\pi_k \mathcal{N}\left(\mathbf{p}_n | \boldsymbol{\mu}_k, \boldsymbol{\Sigma}_k\right)}{\sum_{j=1}^{K} \pi_j \mathcal{N}\left(\mathbf{p}_n | \boldsymbol{\mu}_j, \boldsymbol{\Sigma}_j\right)} \tag{5.10}$$

Where γ_{nk} is node n responsibility to kth cluster and takes values between 0 and 1.

At the second step, the EM algorithm evaluates K weighted center of gravity of a 2-dimensional location vector of nodes. This evaluation uses the responsibility value as weight of nodes.

At the third step, the locations of the cluster centroids are changed to the weighted centers of gravity evaluated in the second step.

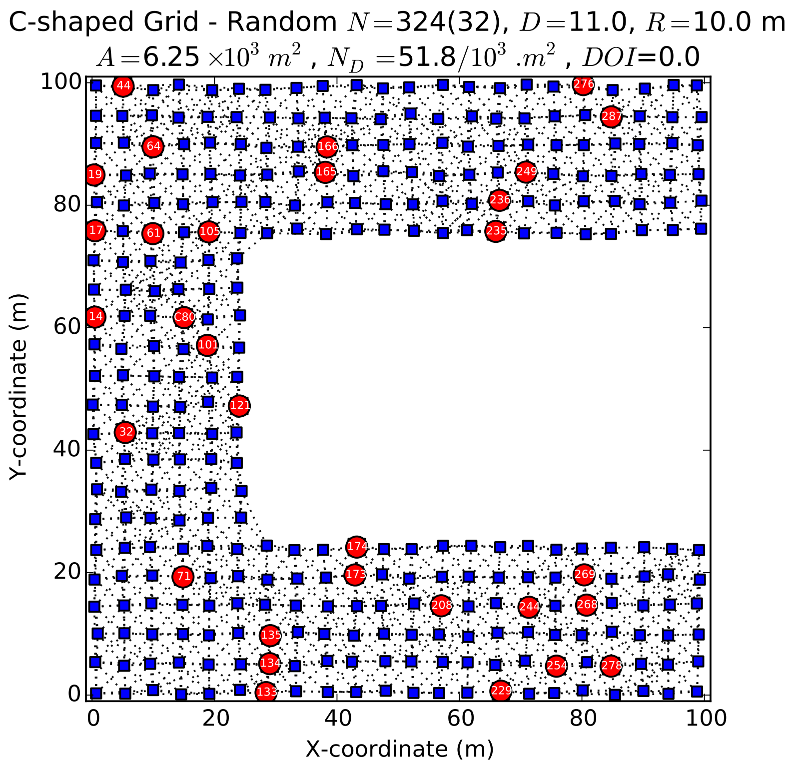
Finally, the EM algorithm evaluates the value of the log likelihood as shown below.

$$\begin{aligned}
\mathcal{P} &= \ln p(\mathbf{X} | \boldsymbol{\mu}, \boldsymbol{\Sigma}, \boldsymbol{\pi}) \\
&= \sum_{n=1}^{N} \ln \left\{ \sum_{k=1}^{K} \pi_k \mathcal{N}(\mathbf{p}_n | \boldsymbol{\mu}_k, \boldsymbol{\Sigma}_k) \right\}.
\end{aligned}$$

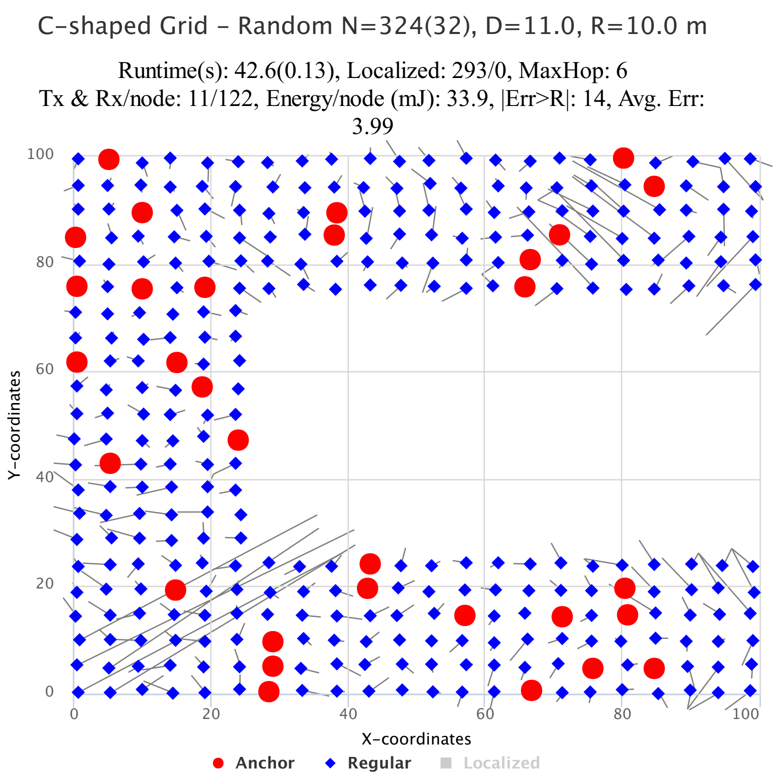
The EM algorithm repeats all steps, until the value of log likelihood converges. The cluster centroids μ_k are used to place the anchors. This usually give a more uniform distribution of anchors as compared to grid scheme for most topologies.

Simulation of Anchor Distribution Strategy

We arbitrary choose a C-shaped network for this simulation. We first generate a C-shaped topology with 324 nodes and then distribute the anchors (with $A_r = 10\%$) using

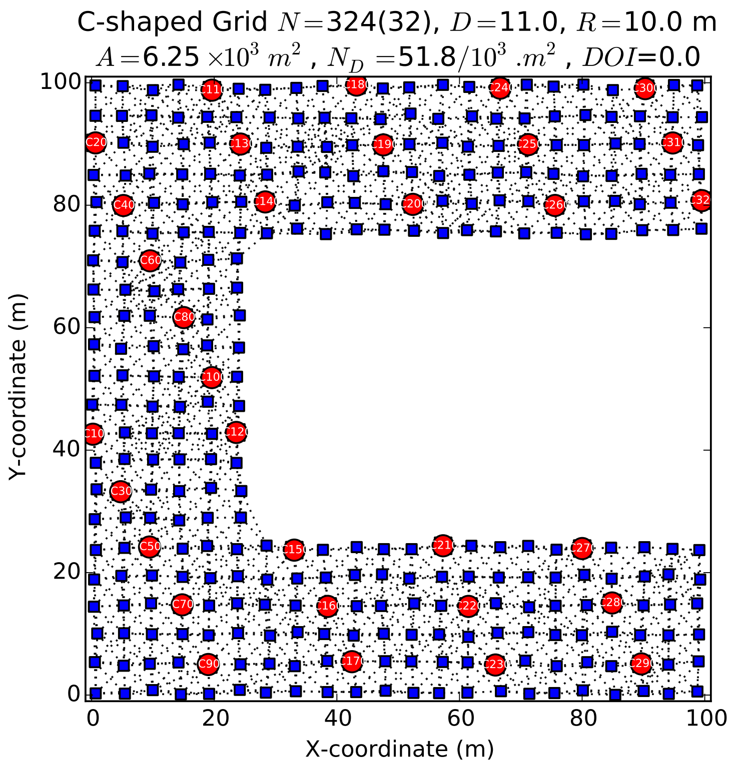


(a) C-shaped Network with Random Anchor Distribution

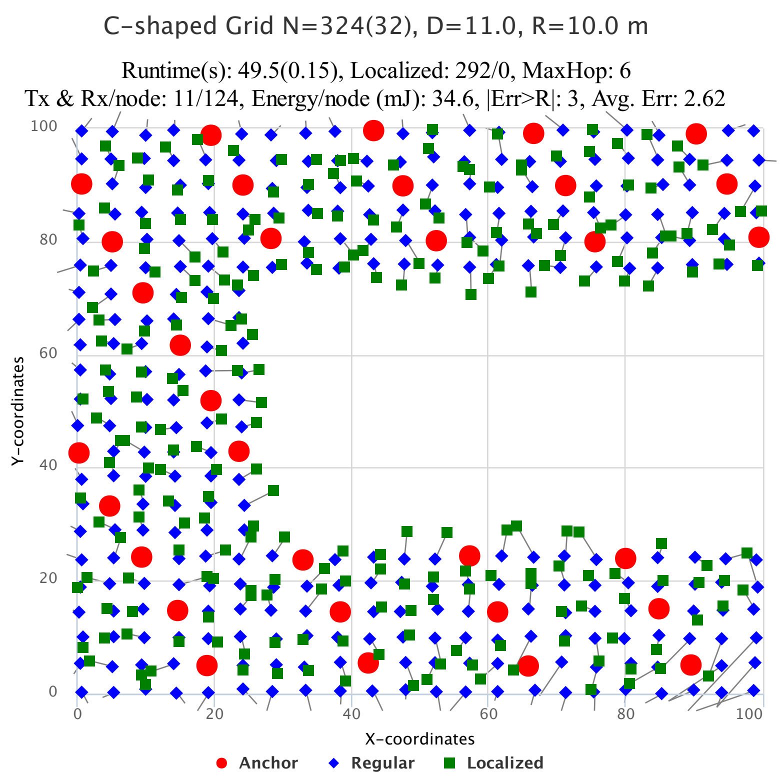


(b) C-shaped Network: Simulation output for DV-maxHop

Figure 5.15: Random Anchor Distribution

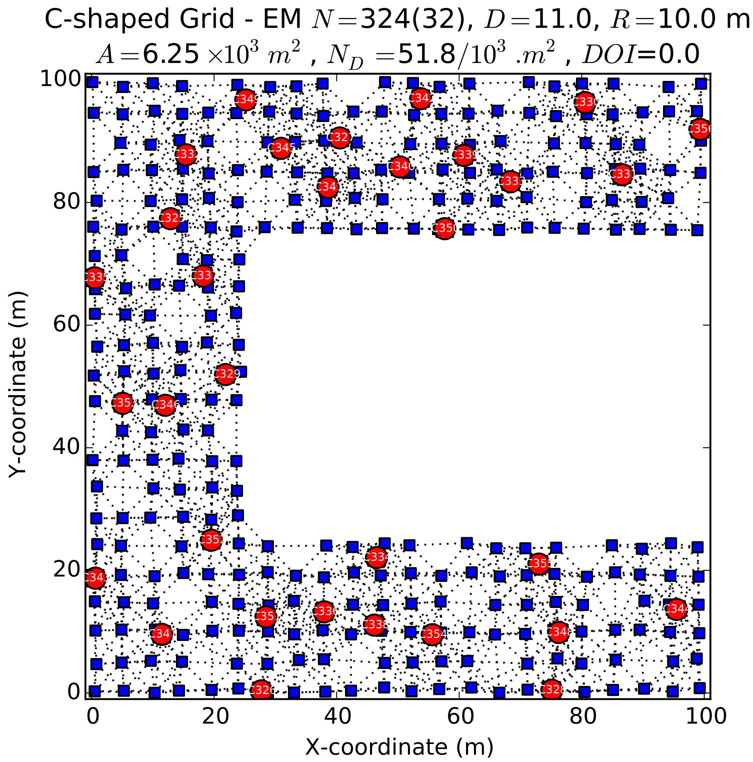


(a) C-shaped Network with Grid Anchor Distribution

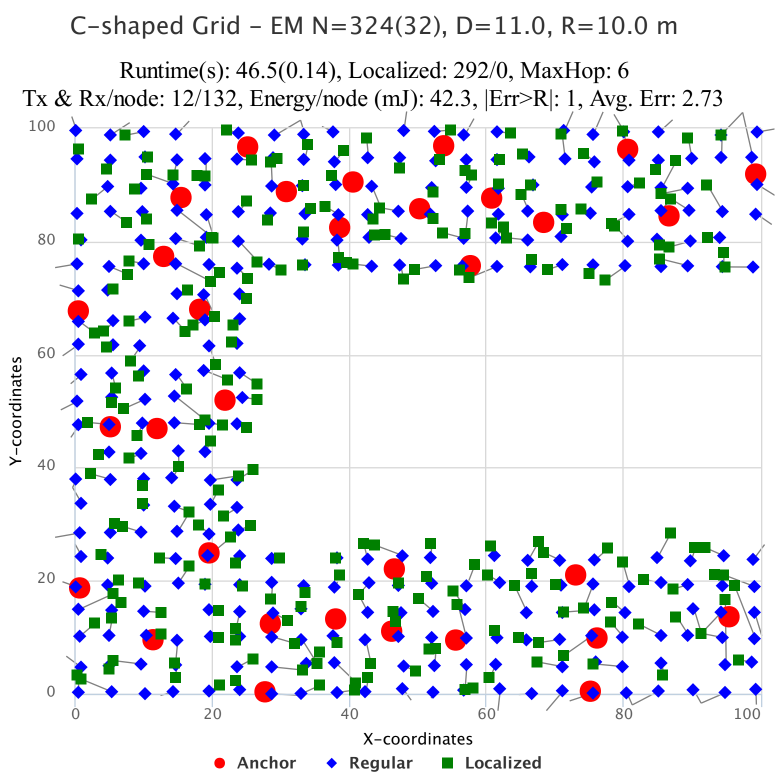


(b) C-shaped Network: Simulation output for DV-maxHop

Figure 5.16: Grid Anchor Distribution



(a) C-shaped Network with Clustered Anchor Distribution



(b) C-shaped Network: Simulation output for DV-maxHop

Figure 5.17: Clustered (EM) Anchor Distribution

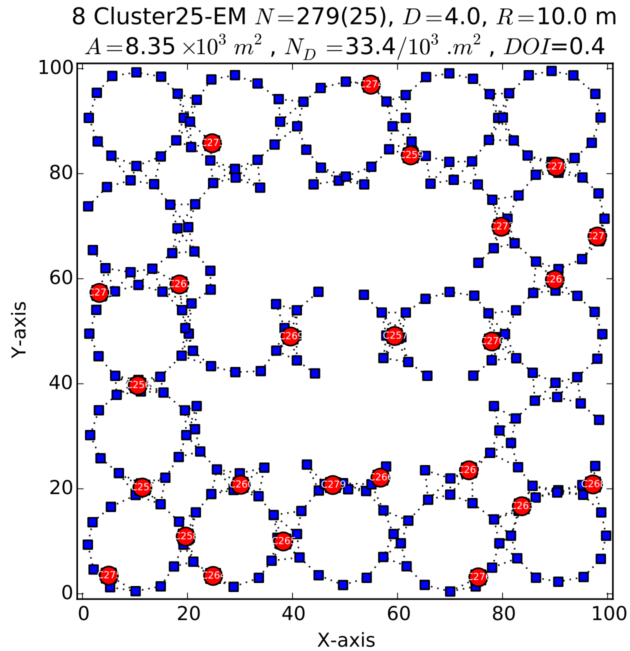
all three strategies mentioned in the previous section. We use $MaxHop$ equals to 6 for all three scenarios. We added the EM clustering module in our simulation framework. The topologies are shown in Figs. 5.15a, 5.16a 5.17a and corresponding simulation results on the topological charts are shown in Figs. 5.15b, 5.16b 5.17b. As expected, the random scheme has the worst performance. Average error is 3.99 m (or $0.399R$) with 14 nodes have localization errors above R.

The grid and clustered anchor distribution results are comparable. While average localization error is little less for grid ($0.26R$ vs. $0.273R$), the errors are more distributed in clustered anchor approach. Only one node has errors above R in clustered deployment whereas there are three in grid deployment. The clustered distribution also results in little faster convergence but has little higher energy cost.

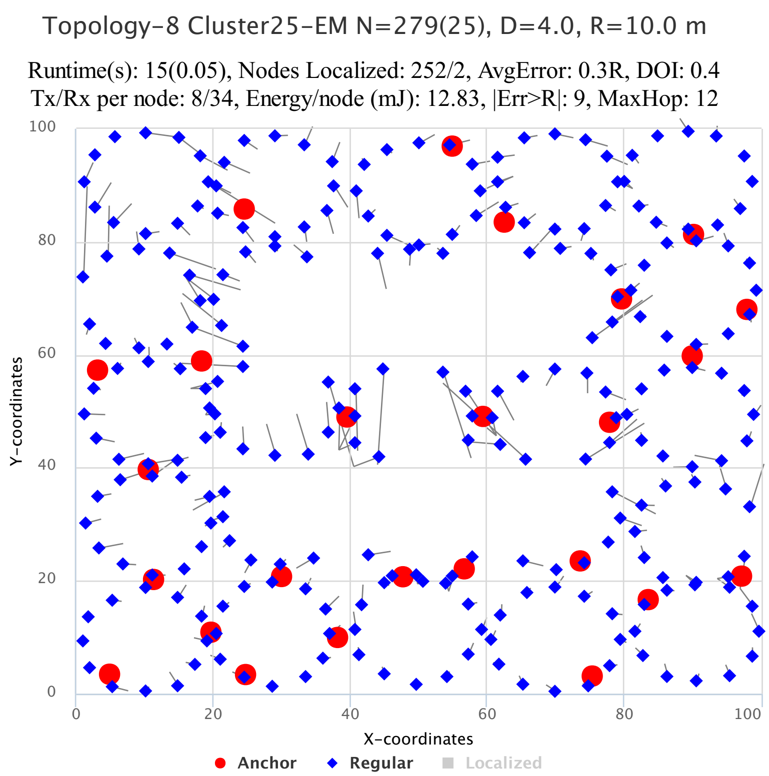
In some scenarios, manual anchor distribution may be the only feasible option to achieve optimal performance.

5.5.7 A Realistic Scenario

Now we consider a real world deployment scenario where nodes are deployed in a oil/gas facility with buildings, equipments and terrain causing multiple anisotropy due to holes, non-uniform distribution of nodes, sparsity in the network and irregular communication patterns (DOI=0.4). As can be seen from Fig. 5.18a, there are two bigger holes (buildings) in the middle and there are several equipments (circular) around which nodes are installed forming a pseudo-cluster topology. Since, in this deployment, we can estimate the approximate location and number of nodes in certain section of the network, we use



(a) A realistic network topology for an oil/gas facility



(b) Simulation output for DV-maxHop with $MaxHop$=12

Figure 5.18: A real world deployment scenario with nodes forming a pseudo-cluster topology around equipments.

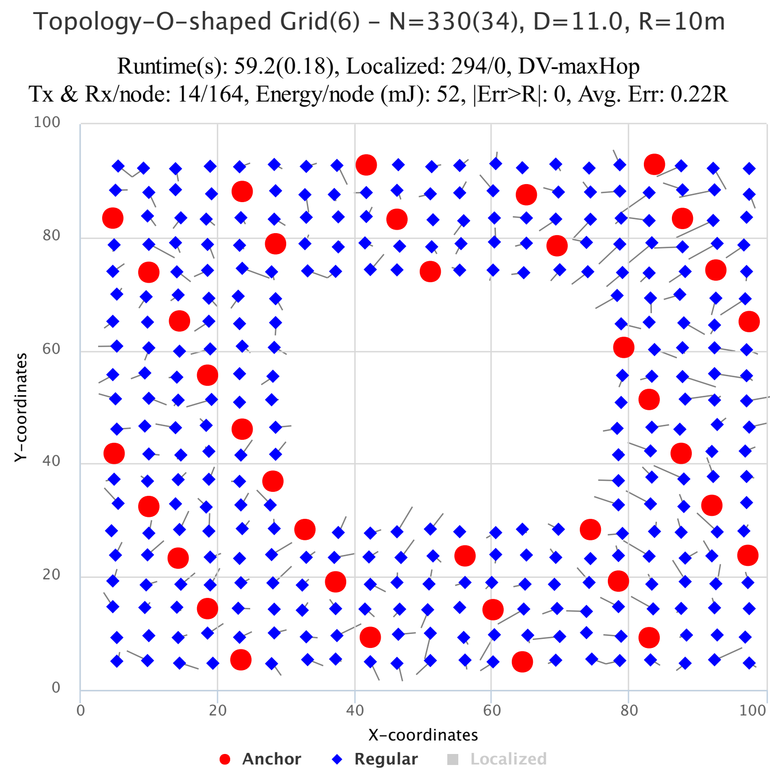
EM clustering to place the anchors. We choose 25 clusters and their centroids are the location of the anchors. These anchors (about 8% of total sensor nodes) are mostly on the bottom part of the network. Due to sparsity, non-uniform node distribution and DOI of 0.4, the average degree is only 4. Fig. 5.18b shows the simulation results. Our scheme still provide good results with average error of $0.296R$ with only 9 nodes having errors above R. Two nodes are not localized due to low connectivity and nodes on the top and middle have greater errors due to less number of anchors. We use a little higher value of $MaxHop$=12 as low connectivity means we require some farther anchors to provide position information to get the optimal accuracy.

5.5.8 Multi-objective Optimization Simulations

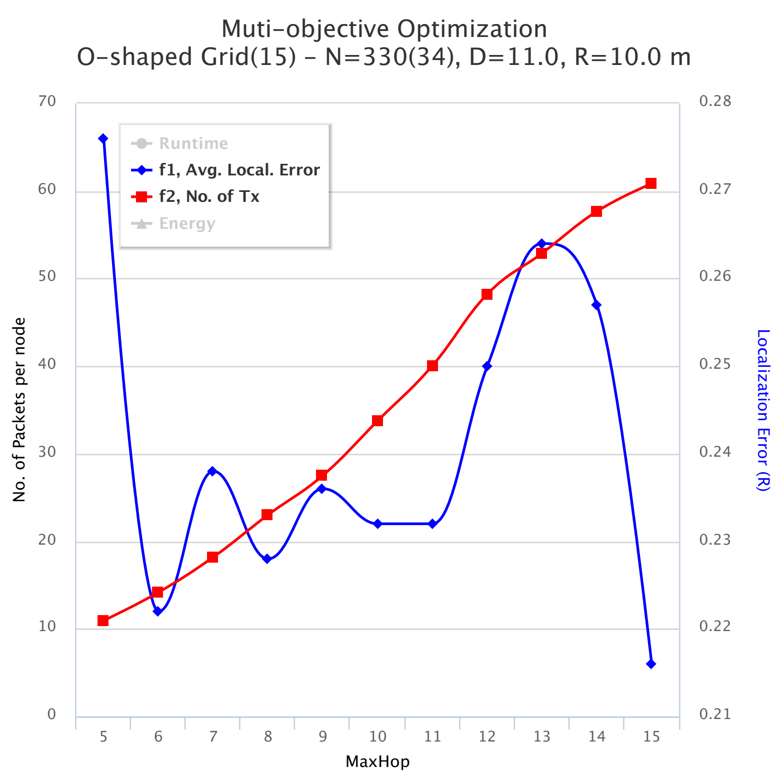
In the section, we present the best possible solutions for minimization of equation 5.8 using simulations on several topologies.

Fig. 5.19a shows the topology and localization results for an O-shaped network with 330 nodes including 34 anchors. Fig. 5.19b plots the objective functions of equations 5.6 and 5.7 versus $MaxHop$ showing possible solutions. The optimal solution is for $MaxHop$=6 with average localization error around 0.22R and number of transmission around 14 per node. All other related statistics are shown in Fig. 5.19a. We do see a little lower error (about $0.215R$) for $MaxHop$=15 but at a much higher communication cost (about 61 transmissions per node).

Similarly, Fig. 5.20a shows the topology and localization results for an C-shaped network with 306 nodes including 30 anchors. Fig. 5.20b plots the objective functions of



(a) Localization results for an O-shaped Network with $MaxHop$=6



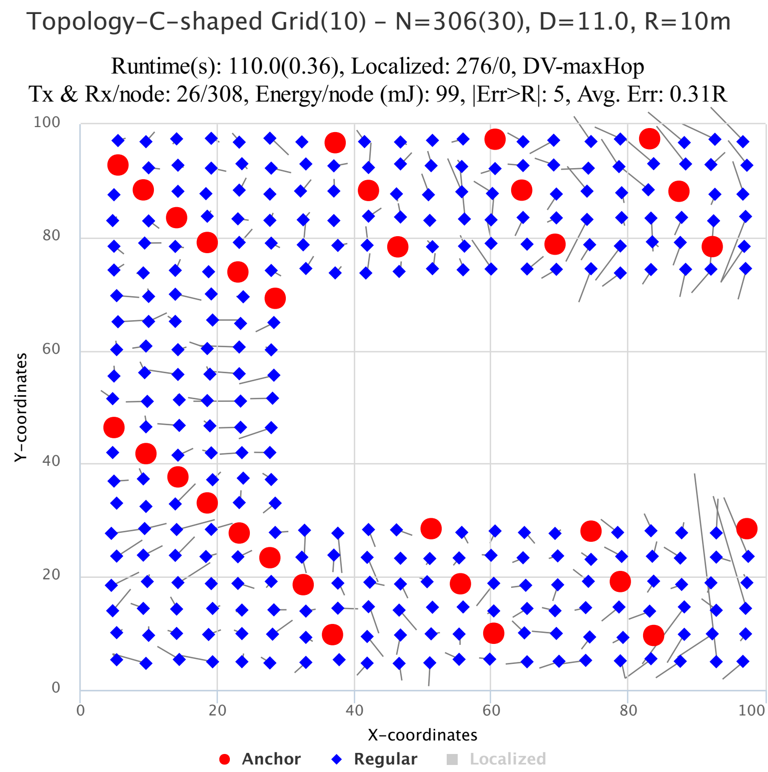
(b) Objective functions possible solutions

Figure 5.19: Multi-objective Optimization Simulation results for an O-shaped Network.

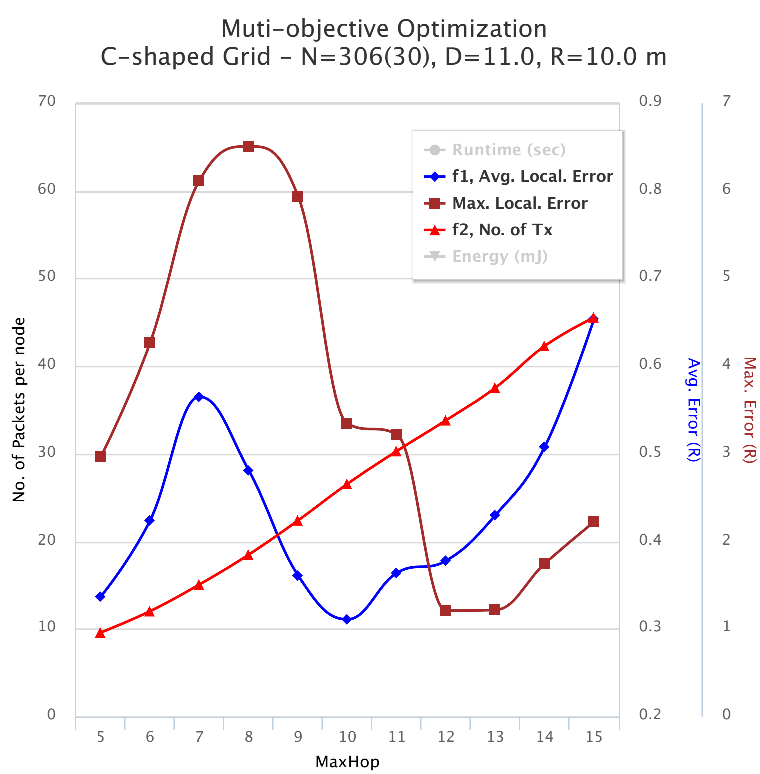
equations 5.6 and 5.7 versus $MaxHop$ showing possible solutions. The optimal solution seems to be for $MaxHop$=10 with average localization error around $0.31R$ (max. error is about $3.34R$) and number of transmission around 26 per node. However, much faster and energy efficient solution is obtained for $MaxHop$=5 with little higher average error and lower maximum error of $2.96R$. All other related statistics are shown in Fig. 5.20a. Another solution could be for $MaxHop$=12 with lowest maximum error of $1.2R$ but little higher average error and transmission cost.

Fig. 5.21a shows the topology and localization results for a S-shaped network with 343 nodes including 34 anchors. Fig. 5.21b plots the objective functions of equations 5.6 and 5.7 versus $MaxHop$ showing possible solutions. The optimal solution is for $MaxHop$=7 with average localization error around 0.346R and number of transmission around 14 per node. All other related statistics are shown in Fig. 5.21a.

Finally, Fig. 5.22a shows the topology and localization results for a sparse network with 81 nodes including 6 anchors. Fig. 5.22b plots the objective functions of equations 5.6 and 5.7 versus $MaxHop$ showing possible solutions. The optimal solution is for $MaxHop$=9 with average localization error around 0.25R and number of transmission around 7.7 per node. All other related statistics are shown in Fig. 5.22a. Another solution could be for $MaxHop$=12 but with little higher transmission cost of 8.72 packets per node.

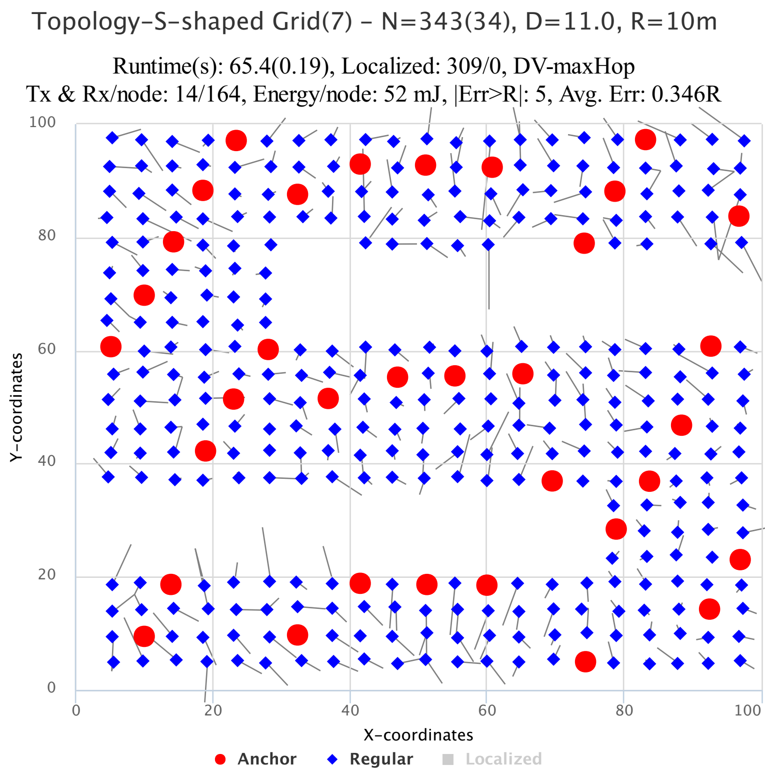


(a) Localization results for a C-shaped Network with $MaxHop$=10

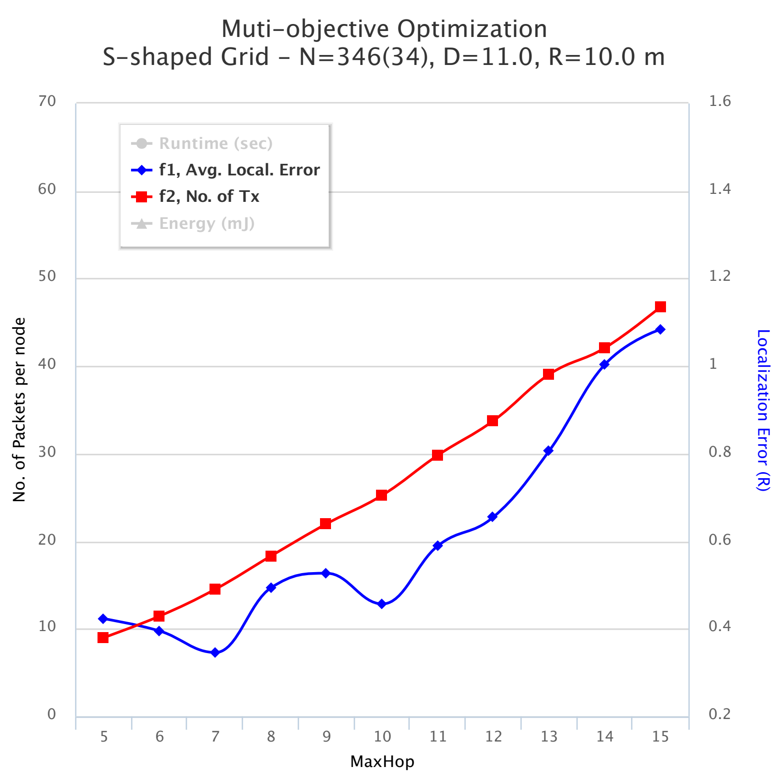


(b) Objective functions possible solutions

Figure 5.20: Multi-objective Optimization Simulation results for a C-shaped Network.

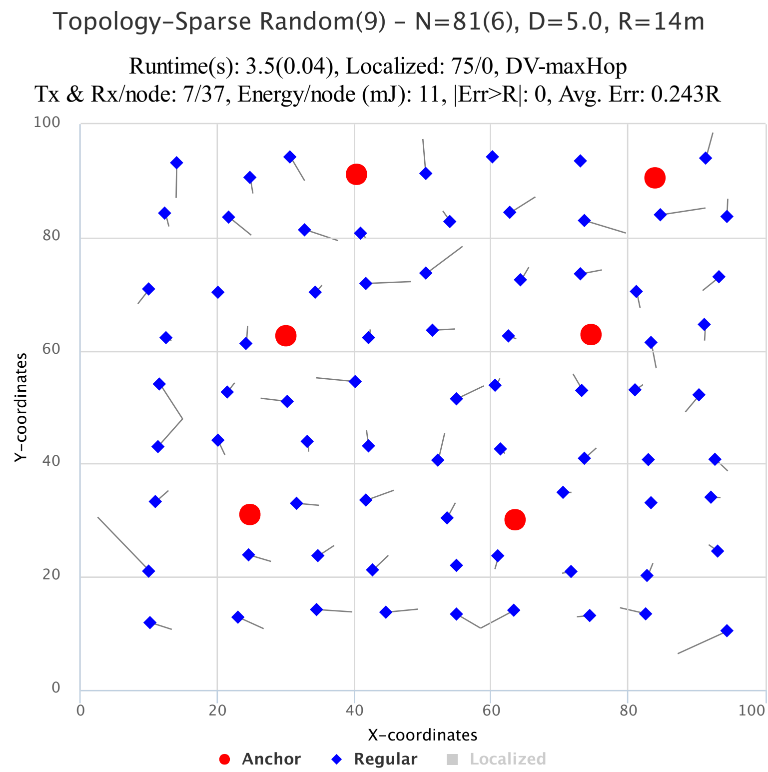


(a) Localization results for a S-shaped Network with $MaxHop$=7

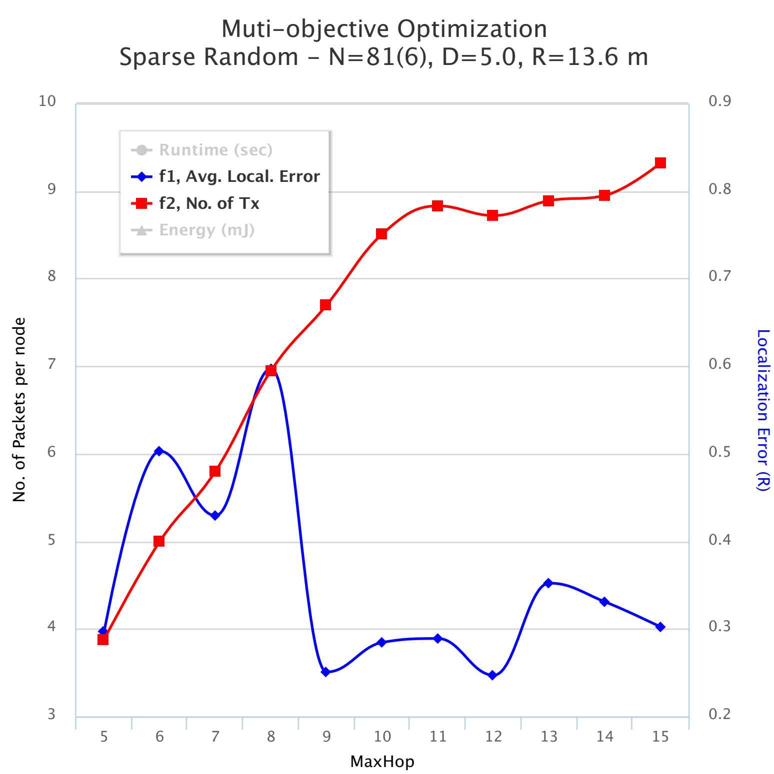


(b) Objective functions possible solutions

Figure 5.21: Multi-objective Optimization Simulation results for a S-shaped Network.



(a) Localization results for a Sparse Network with $MaxHop$=9



(b) Objective functions possible solutions

Figure 5.22: Multi-objective Optimization Simulation results for a Sparse Network.

5.6 Conclusion

The development of a reliable and robust large-scale wireless system requires that the design concepts be checked and optimized before they are implemented and tested for a specific hardware platform. Simulation provides a cost-effective and feasible method of examining the correctness and scalability of the system before deployment. The focus of this work was to extensively simulate range-free localization algorithms. First, we used our topology generator module to generate several isotopic and anisotropic networks based on desired connectivity, network density and communication range. Then, we employed our extended Pymote framework to carry out very comprehensive localization algorithm simulations to collect several statistics by varying several control parameters. The results are analyzed statistically and visually using interactive charts and plots. In this work, we have presented a framework and guidelines which illustrate the importance of systematic and visual analysis of simulation results.

Then we proposed an enhancement to the pioneer distance vector or DV-Hop algorithm to estimate node localization for anisotropic networks. The recently-proposed algorithms for anisotropic networks provide good estimation but are complex with communication and computational overheads and may be unfeasible or undesirable for low-cost, low-power, location-dependent protocols and applications. Our scheme, called DV-maxHop, reached good accuracy quickly utilizing a simpler, practical and proven DV-Hop-based algorithm. We formulated multi-objective optimization to achieve better accuracy and efficiency. We utilized our Pymote simulation framework to extensively simulate range-free localization algorithms. The comprehensive and interactive simulation results provided statistical and visual analysis and comparison of range-free localization algorithms. Our scheme results in improved localization accuracy and efficiency in anisotropic and isotropic wireless networks of different types, with much faster convergence and low overheads when compared to existing algorithms. We also study and simulate some anchor distribution strategies and compare their performance.

CHAPTER 6

PROOF-OF-CONCEPT PROTOTYPE AND WEB APPLICATION

The objective of this chapter is to design and implement a smart WSN-based system, combined with RF and satellite technology, to monitor and detect gas leakage in a oil/gas industry. This project implements an end-to-end solution to send information from the sensor nodes installed in the fields to the user via Internet. This includes components for the development of a script on the satellite terminal, back office application including XML, database interface to receive/process the incoming data from the satellite system, and an interactive web application.

6.1 Project Implementation

The system overview is shown in Fig. 6.1. The different components are shown in dotted rectangles. In this project, we need to work on following four tasks:

1. Design and implementation of gas leakage detection system using wireless sensor nodes and gas sensors. This consists of a base station and a few sensor nodes with gas sensor to detect gas concentration due to leakage into the surroundings.

2. Programming of the satellite terminal to interface with the gas leakage detection system via base station generally referred to as WSN in this chapter.

3. XML gateway interface - Receive/send/decode messages from the service provider (Honeywell's message handling system) and store the data in the database. The MySQL database is installed and configured on the College of Computer Science and Engineering (CCSE) Unix server.

4. An interactive web application - To retrieve data from database and display /analyze the information using tables, maps, charts and graphs and to develop the web application using PHP which is hosted on the CCSE server.

6.2 Satellite Monitoring

6.2.1 Inmarsat Geostationary Satellites

The Honeywell system utilizes INMARSAT geostationary satellites to provide a global IsatM2M service [96]. These include Atlantic Ocean Region East (AORE), Atlantic

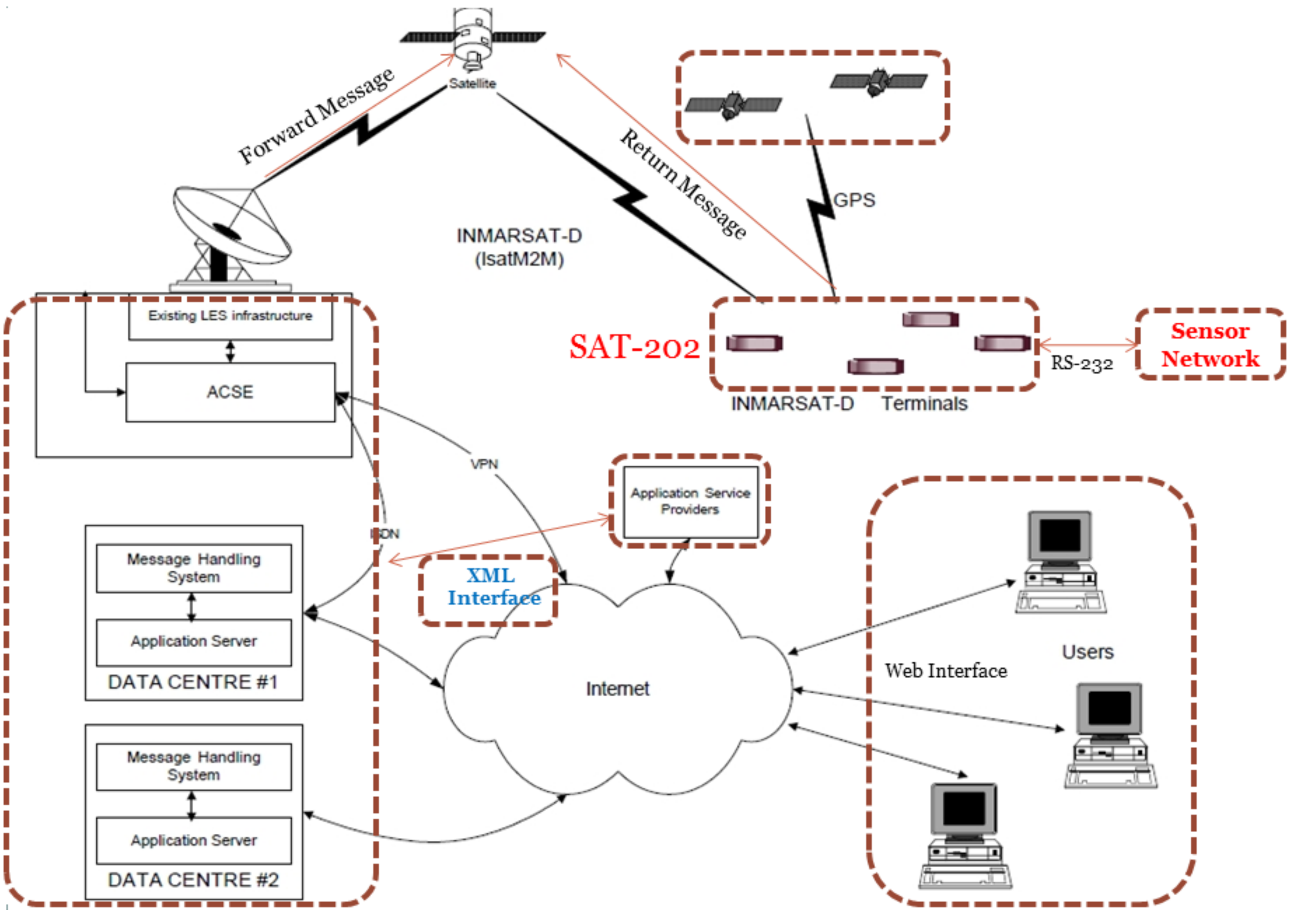


Figure 6.1: System Overview

Ocean Region West (AORW), Indian Ocean Region (IOR) and Pacific Ocean Region (POR) as shown in Fig. 6.2. The GPS constellation of 24 satellites is designed so that a minimum of five are always observable by a user anywhere on earth. The receiver uses data from the best four satellites above the horizon, adding signals from one as it drops signals from another, to continually calculate its position.

6.2.2 The IsatM2M Protocol

INMARSAT-D incorporates modes of operation which are commonly referred to as D+ and IsatM2M. The D+ mode adds return (from terminal) messaging capability to

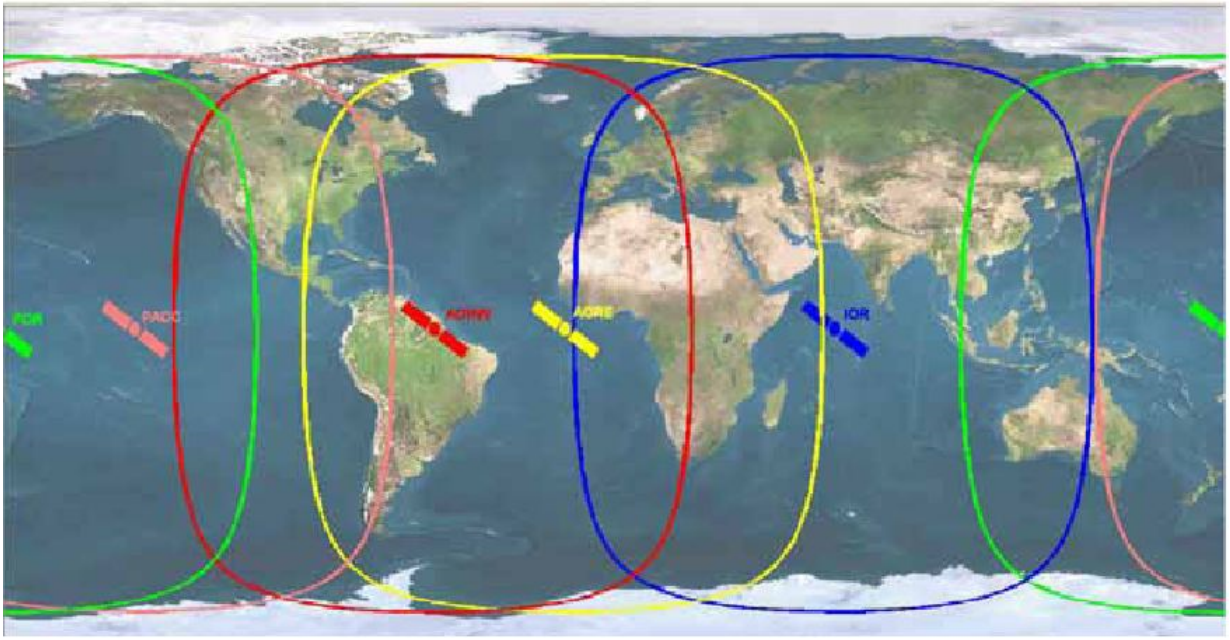


Figure 6.2: Inmarsat Ocean Regions

INMARSAT-D. In addition to return messaging capability, the IsatM2M mode also provides increased data rates and reduced message delivery latency. Information to and from terminals is transmitted on discrete channels. When a Terminal first powers up it must determine which channels to use for receiving and transmitting. Every Terminal is assigned an ISN (Inmarsat Serial Number). This number is used to uniquely identify a terminal for the purposes of message delivery. At the application level, the ISN is mapped to an AdC (Address Code) which is simply a unique code assigned by the service provider in a format of its choice [96]. For a terminal to receive/transmit messages, it must also be configured with the correct SID (Service Identifier) this would normally be programmed by the service provider prior to shipment. Each satellite (Ocean Region) transmits a Bulletin Board' on a known frequency. The Bulletin Board channel provides the information necessary to enable a terminal to tune to the correct Traffic channel as determined by its SID. Messages to terminals are carried on a Traffic Channel. The

Traffic channel also provides information to the terminal regarding channel it may use for transmission. Once a terminal has acquired a Bulletin Board, it stores the channel allocation information such that for subsequent acquisitions of the IsatM2M service, the terminal can tune directly to the appropriate Traffic channel.

6.2.3 Honeywell Global Tracking System

The SAT-202 satellite terminal from Honeywell Global Tracking is a multipurpose satellite terminal for tracking and monitoring high-value assets like vehicles, vessels, cargo and personnel [97]. The services provided by Honeywell for these devices include:

- Global Coverage: Secure satellite connectivity worldwide
- Inmarsat and GPS Connectivity: Tracking, monitoring and communicating with mobile assets anywhere in the world.
- Affordable and Reliable: Enables field-proven and cost-effective tracking solutions for a wide range of applications.
- Flexible Mapping: Facilitates viewing of assets using Google and Bing maps in a standard browser, or integrates data feeds into custom enterprise resource planning (ERP) solutions.
- Multiple I/O Ports (Add-ons): Allows connected external sensors to report additional data, e.g., speed, tire pressure, and fuel consumption; ideal for fleet management applications [98].

6.3 Interface between SAT-202 & WSN

6.3.1 RS-232 Interface & Messaging

Utilizing the RS-232 specifications (9.2 kbps baud, 8-N-1) the SAT-202 terminals are configured to send/receive data to/from the satellite [99]. Inmarsat-M2M network supports three types of Return Channel messages (that is, data sent from a remote terminal, back to the Land Earth Station); Long, Double and Acknowledgment bursts. Of these, the Acknowledge Burst cannot contain any user data. The Double burst is actually transmitted as two standard Long bursts. Although Return Channel bursts are binary data, they are often written as hexadecimal strings and indeed, this is how they are retrieved from the MHS via the ASPI-XML Interface. A typical Long burst is written as twenty-one hexadecimal characters, for example: 90 08 C3 3E CC 40 89 AE 00 B1 8

6.3.2 Quality of Service

Forward messages are the messages sent to the terminals, and are stored and forwarded. Quality of Service is therefore measured by queue delay (latency). If there are no queuing delays then average latency for an IsatM2M forward channel message is 45 seconds.

Return messages are the messages requested from the terminals, so are accessed randomly (on user demand) and Quality of Service is hence measured by the number of messages lost due to collisions. Collisions occur when two or more terminals transmit at exactly the same time on exactly the same frequency. Terminals minimize the probability of collision by:

- Randomizing transmission time, and
- Randomizing their transmit frequency within the allocated return channel bandwidth.

The SAT-202 terminal ensures that enough return channel bandwidth is made available to maintain an acceptable quality of service in the return direction. Assuming the terminal has already acquired the traffic channel, typical latency for a return message burst, from start of transmission, is less than 10 seconds. These latencies are for the IsatM2M system only and do not take into account other causes of latency that need to be considered when looking at the performance of an end-to-end application. The other main areas of latency to consider are:

- Internet delays.
- Delay from trigger event to the terminal starting a transmission.
- Slot randomization is applied.

6.3.3 Communication between Sat-202 & WSN

The customized script running on the Sat-202 terminals allows an easy interface to send data to it from WSN (base station) [99]. The prototype system is shown in Fig. 6.3. The command serial interface to the terminal is configured as an RS-232, bi-directional, asynchronous serial port operating at 9600 bps, 8 bit data, no parity and 1 stop bit. The interface comprises the two data lines and a signal ground. The sensor data is sent one by one using the following commands (using hexadecimal encoded integer in uppercase):

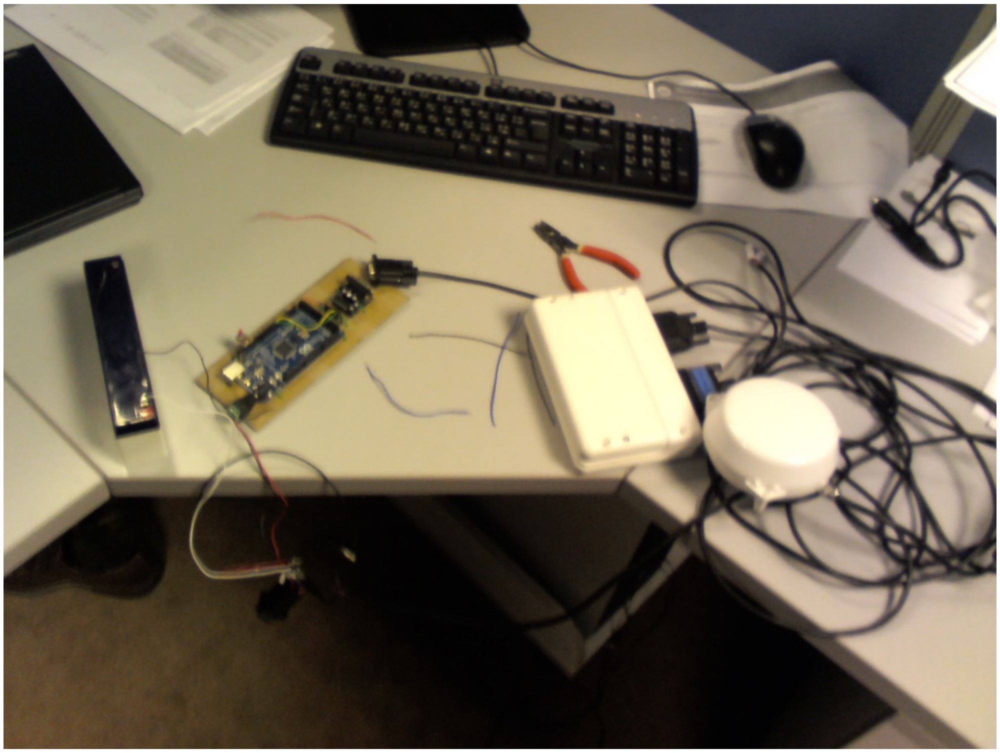


Figure 6.3: Hardware setup of SAT-202 terminal with Arduino Micro-controller (WSN Sink)

1. SR A <2-byte sensor 1 data in hexadecimal format>//ex. SR A 0045
2. SR B <2-byte sensor 2 data in hexadecimal format>//ex. SR B 00AC
3. SR C <2-byte sensor 3 data in hexadecimal format>//ex. SR C 10B8
4. SR 9 <1-byte node Id in hexadecimal format>//ex. SR 9 D
5. MB D9 //Transmit Data Message optional (see below)
6. Each command ends with <CR>.

The terminal will echo back the command in the lower case (if there are no errors) for each command. The application running on the WSN sink, can decide to just update the data for sensors without the request to send the message. In case the sink reads a higher value for dust, it can send the request to transmit the message right away. Moreover, to control the message rate from satellite terminal, the sink can accumulate the sensor data from each node (like average or maximum) and send only one message with node Id set to 0xFF.

6.3.4 Communication between SAT-202 and Satellites

The custom script running on the Sat-202 terminals have timers running for sending messages at a preset interval. There are two types of messages supported: Gas sensor report (Table 6.1), and GPS report (Table 6.2). After one minute of booting, a GPS message is sent.The normal reporting timer is set to report every hour. In case of alerts, the reporting timer is set to report every 10 minutes. The alert is activated by grounding (0 V) the high-Z digital input. All these timers can be modified by over-the-satellite forward message. Terminal can also be polled on demand to send either GPS or data message.

Bits	**Size**	**Field Name**	**Comments**
0 -3	4	Control Flags = 0	
4-11	8	Message Identifier	Node Ids / Event codes
12-19	8	Message Type = 0x8C	Sensor Data Message
20-35	16	Sensor 1 Data	2 bytes (integer)
36-51	16	Sensor 2 Data	2 bytes (integer)
52-67	16	Sensor 3 Data	2 bytes (integer)
68-83	16	Sensor 4 Data	2 bytes (integer)

Table 6.1: Message Format - Gas Sensor Report

Bits	Size	Field Name	Comments
0..3	4	Control Word = 9	Built-In Type
4..11	8	Canned Message Code	(0 127)
12..19	8	Message Identifier = 1	Marine Position Report
20..40	21	Latitude	20: Hemisphere N/S (0 = +ve; 1 = -ve) 21..27: Degrees; 28..33: Minutes 34..40: Hundredths of a Minute
41..62	22	Longitude	41: Hemisphere E/W (0 = +ve; 1 = -ve) 42..49: Degrees; 50..55: Minutes 56..62: Hundredths of a Minute
63..70	8	Speed	Kilometers per Hour
71..79	9	Heading	Degrees
80	1	GPS Status	0 = Invalid; 1 = Valid
81..83	3	Last Fix	Hours since last valid GPS

Table 6.2: Message Format - GPS Report

6.4 Gateway communication client (GCC)

The messages sent by the SAT-202 terminals, through the satellites, are then stored in the Message Handling System (MHS) of Honeywell. As an Application Service Provider (ASP), we are required to interact with the MHS Gateway to fetch our desired data. This Gateway Communication Client (GCC) is designed with following features:

1. Around the globe accessibility (through Internet),
2. Operability - On-demand, or as a Running Background Process.

6.4.1 Significance of the Gateway Communication Client (GCC)

The role of the GCC is like a middle-layer application. The data is sent from the WSN through the SAT-202 terminals, via the satellites, and into the Honeywell's MHS. The

GCC sends requests to the MHS to get the satellite terminals' readings through the ASP (client) and inserts the incoming messages to the users' database. From the users' perspective, this database and the web interface can be accessed and used from any part of the world via the Internet to view the data in a graphical and meaningful way.

6.4.2 XML Gateway Interface

The GCC sends requests to get the users' satellite terminals' readings through our ASP (client) for info from MHS (server) via well-formed XML [100]. The MHS (server) responds to the client via another XML string which contains the requested information.The client application parses the XML string for needed information and decodes the received bytes into meaningful values for storage into a database (according to the Message Format descriptions). Then, the MySQL database (from which the web user interface would fetch data for the user) is updated by writing the decoded information into the respective tables/values. The MHS servers run ASPI-XML/3.2 which is the latest Version of ASP interface based on request and response paradigm.

6.4.3 Client Server Communication

The different types of messages allowed for the client to send to the MHS and their corresponding responses are shown in Table 6.3.

The most relevant of these are the RequestDelivery and MessageDelivery.

1. XML Request (Client to Server)

ASP Request	MHS Response
SubmitMessage	StatusReport
RequestStatus	StatusReport
CancelMessage	StatusReport
RequestDelivery	MessageDelivery
GetMessageCopy	Message Copy
GetLastIdentifier	LastIdentifier

Table 6.3: ASP request/response

```
<RequestDelivery qos="">
<Authentication id="">...</Authentication>
<ForwardMessagenid="" limit="" />
<ReturnMessage rid="" limit="" />
</RequestDelivery>
```

2. XML Response (Server to Client)

```
<MessageDelivery>
<ForwardMessagenid="" fid="">
        <MessageStatus code="" time="">...</MessageStatus>
</ForwardMessage>
<ReturnMessage rid="">
        <AdC ocean="">...</AdC>
        <MessageData>...</MessageData>
        <MessageStatus code="" time="">...</MessageStatus>
        <Flags les="" app="" />
</ReturnMessage>
</MessageDelivery>
```

6.5 Web Application

- User can login to the secured website with a user-name and password.
- The web application displays the current status of all the assets assigned to the user.
- The information is retrieved from the database.

- User can see the history of any specific asset or see more detailed analysis of data via graphs, charts or maps.
- The web application support interactive Google maps (via JavaScript based API), Google Earth (kml files) and Excel sheet download.
- The web application utilizes DHTML, PHP, JavaScript, jQuery and CSS for dynamic content of the web interface.
- Location of the website: `http://www.ccse.kfupm.edu.sa/~gr199305420/gas/`

6.5.1 Web App Options/Pages

- Fleet Report: The overall current status of all units. It provides links to history, Google maps, Google earth and excel download.
- Message History: The list of messages for any specific unit. It provides links to Google maps, Google earth and excel download.
- Google Maps: Interactive display of the unit's location on Google maps and provides option for centering, zooming and distance calculation, etc.
- Google Earth Interface: Interface with the Google Earth thick client(via KML files) to provide more detailed mapping with options to include layers for 3D objects, traffic, weather and other data.

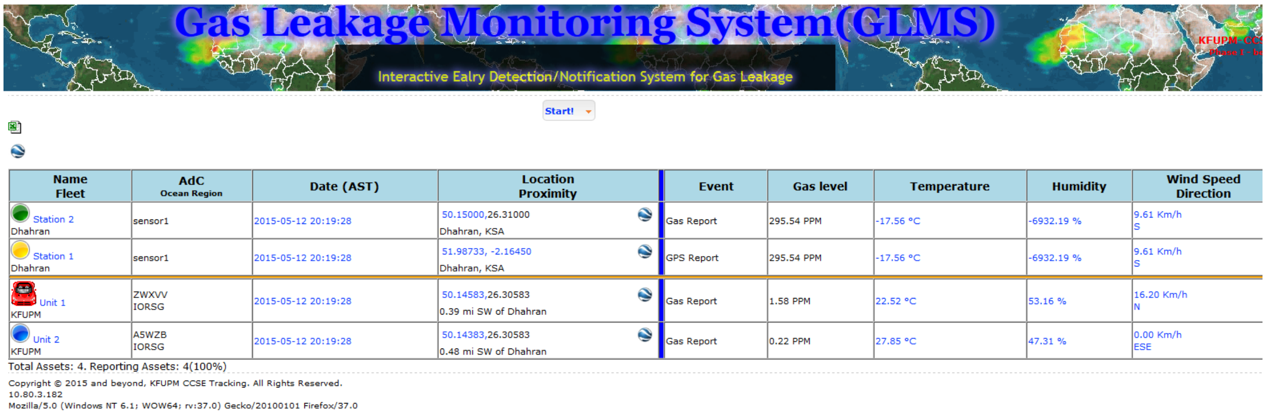
- Excel download: Provide the option to download the data from web application to excel for further analysis and storage.
- Forward Command (polling): On-demand polling of GPS or sensor data.
- Asset Activation: Allow easy setup/activation of newly installed satellite terminal.
- Asset Management: Allow updating the info related to any specific unit.
- XML gateway status: Display the status of XML gateway application.

6.5.2 Web Screen shots

In this section, some screen shots of the web application are presented including the main tracking page, command page, and Google map/earth views.

6.6 Conclusion

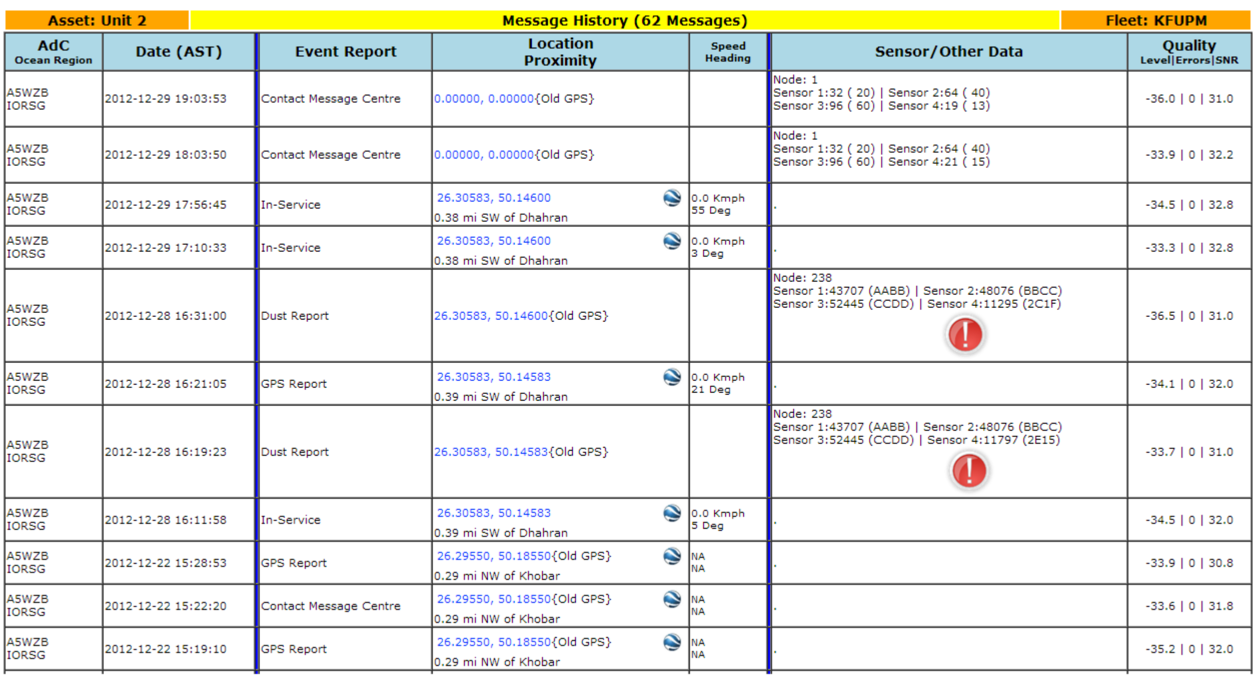
In this chapter, a solution for remote monitoring of wireless sensor network is presented. The implementation details of the satellite monitoring solution are also discussed. The project implementation was divided in three tasks or layers for easier and modular development. The first task of interfacing the satellite terminal with the WSN requires understanding of serial/RS232 communication and scripting language. The second task or middle layer involves client-server programming, XML parsing, information encoding/decoding, and database/SQL programming. The third task or application layer consist of an interactive web application utilizing database access, dynamic pages, client side scripts (javaScripts) and GIS (mapping and Google earth interface). The web application is accessible from the Internet and provides real-time data analysis and notification via email or SMS.



Name Fleet	AdC Ocean Region	Date (AST)	Location Proximity	Event	Gas level	Temperature	Humidity	Wind Speed Direction
Station 2 Dhahran	sensor1	2015-05-12 20:19:28	50.15000,26.31000 Dhahran, KSA	Gas Report	295.54 PPM	-17.56 °C	-6932.19 %	9.61 Km/h S
Station 1 Dhahran	sensor1	2015-05-12 20:19:28	51.98733, -2.16450 Dhahran, KSA	GPS Report	295.54 PPM	-17.56 °C	-6932.19 %	9.61 Km/h S
Unit 1 KFUPM	ZWXVV IORSG	2015-05-12 20:19:28	50.14583,26.30583 0.39 mi SW of Dhahran	Gas Report	1.58 PPM	22.52 °C	53.16 %	16.20 Km/h N
Unit 2 KFUPM	A5WZB IORSG	2015-05-12 20:19:28	50.14383,26.30583 0.48 mi SW of Dhahran	Gas Report	0.22 PPM	27.85 °C	47.31 %	0.00 Km/h ESE

Total Assets: 4. Reporting Assets: 4(100%)

Figure 6.4: Fleet Report - main page



Asset: Unit 2			Message History (62 Messages)			Fleet: KFUPM
AdC Ocean Region	**Date (AST)**	**Event Report**	**Location** **Proximity**	**Speed** **Heading**	**Sensor/Other Data**	**Quality** Level|Errors|SNR
A5WZB IORSG	2012-12-29 19:03:53	Contact Message Centre	0.00000, 0.00000{Old GPS}		Node: 1 Sensor 1:32 (20) | Sensor 2:64 (40) Sensor 3:96 (60) | Sensor 4:19 (13)	-36.0 | 0 | 31.0
A5WZB IORSG	2012-12-29 18:03:50	Contact Message Centre	0.00000, 0.00000{Old GPS}		Node: 1 Sensor 1:32 (20) | Sensor 2:64 (40) Sensor 3:96 (60) | Sensor 4:21 (15)	-33.9 | 0 | 32.2
A5WZB IORSG	2012-12-29 17:56:45	In-Service	26.30583, 50.14600 0.38 mi SW of Dhahran	0.0 Kmph 55 Deg	.	-34.5 | 0 | 32.8
A5WZB IORSG	2012-12-29 17:10:33	In-Service	26.30583, 50.14600 0.38 mi SW of Dhahran	0.0 Kmph 3 Deg	.	-33.3 | 0 | 32.8
A5WZB IORSG	2012-12-28 16:31:00	Dust Report	26.30583, 50.14600{Old GPS}		Node: 238 Sensor 1:43707 (AABB) | Sensor 2:48076 (BBCC) Sensor 3:52445 (CCDD) | Sensor 4:11295 (2C1F)	-36.5 | 0 | 31.0
A5WZB IORSG	2012-12-28 16:21:05	GPS Report	26.30583, 50.14583 0.39 mi SW of Dhahran	0.0 Kmph 21 Deg	.	-34.1 | 0 | 32.0
A5WZB IORSG	2012-12-28 16:19:23	Dust Report	26.30583, 50.14583{Old GPS}		Node: 238 Sensor 1:43707 (AABB) | Sensor 2:48076 (BBCC) Sensor 3:52445 (CCDD) | Sensor 4:11797 (2E15)	-33.7 | 0 | 31.0
A5WZB IORSG	2012-12-28 16:11:58	In-Service	26.30583, 50.14583 0.39 mi SW of Dhahran	0.0 Kmph 5 Deg	.	-34.5 | 0 | 32.0
A5WZB IORSG	2012-12-22 15:28:53	GPS Report	26.29550, 50.18550{Old GPS} 0.29 mi NW of Khobar	NA NA	.	-33.9 | 0 | 30.8
A5WZB IORSG	2012-12-22 15:22:20	Contact Message Centre	26.29550, 50.18550{Old GPS} 0.29 mi NW of Khobar	NA NA	.	-33.6 | 0 | 31.8
A5WZB IORSG	2012-12-22 15:19:10	GPS Report	26.29550, 50.18550{Old GPS} 0.29 mi NW of Khobar	NA NA	.	-35.2 | 0 | 32.0

Figure 6.5: Message History for a unit

Select Asset : All Go

Last 12 Commands

Asset Fleet	AdC/ Region/ Slot. Rec.	Status	Status/Schd. (AST) Request Time	Category/ Type	Payload/ Data
Unit 2 KFUPM	A5WZB	Ack. burst Received	2012-12-29 17:56:00 2012-12-29 17:55:30	tone 0	Alert Code 0
Unit 2 KFUPM	A5WZB	Ack. burst Received	2012-12-29 17:50:30 2012-12-29 17:50:09	tone 1	Alert Code 1
Unit 1 KFUPM	ZWXVV	No Ack. burst	2012-12-28 16:13:00 2012-12-28 16:12:37	tone 1	Alert Code 1
Unit 1 KFUPM	ZWXVV	Ack. burst Received	2012-12-28 16:05:00 2012-12-28 16:04:19	tone 1	Alert Code 1
Unit 2 KFUPM	A5WZB	Ack. burst Received	2012-12-22 13:19:00 2012-12-22 13:18:15	tone 1	Alert Code 1
Unit 2 KFUPM	A5WZB	No Ack. burst	2012-12-21 19:42:00 2012-12-21 19:41:16	tone 0	Alert Code 0
Unit 1 KFUPM	ZWXVV	Ack. burst Received	2012-12-21 13:56:30 2012-12-21 13:55:59	tone 1	Alert Code 1
Unit 1 KFUPM	ZWXVV	No Ack. burst	2012-12-21 07:19:00 2012-12-21 07:18:31	tone 0	Alert Code 0
Unit 1 KFUPM	ZWXVV	No Ack. burst	2012-12-20 23:34:30 2012-12-20 23:33:36	tone 1	Alert Code 1
		Ack. burst Received	2012-12-20 22:11:30 2012-12-20 22:11:30	0	unKnown Alert Code 1
		Ack. burst Received	2012-12-20 19:23:30 2012-12-20 19:23:30	0	unKnown Alert Code 1
		Unknown	2000-01-01 03:00:00 2012-12-20 18:43:29		tone Alert Code 1

Figure 6.6: Forward Command page

Start!

Asset List

UnitId	Asset Name	Fleet	AdC	ISN	icon	Unit Type	Last Report	.
0000000002	Station 2	Dhahran	dust2	ABCDE		Dust Monitoring (1)	2012-12-25 10:00:00	Change
0000000001	Station 1	Dhahran	dust1	ABCDE		Dust Monitoring (1)	2012-12-25 00:00:00	Change
0000002662	Unit 1	KFUPM	ZWXVV	DST00579E8D2		Dust Monitoring (0)	2012-12-28 13:09:30	Change
0000002663	Unit 2	KFUPM	A5WZB	DST005CCBD82		Dust Monitoring (0)	2012-12-29 16:03:53	Change
Total Assets			4	.	..	..		

Figure 6.7: Unit/Asset management

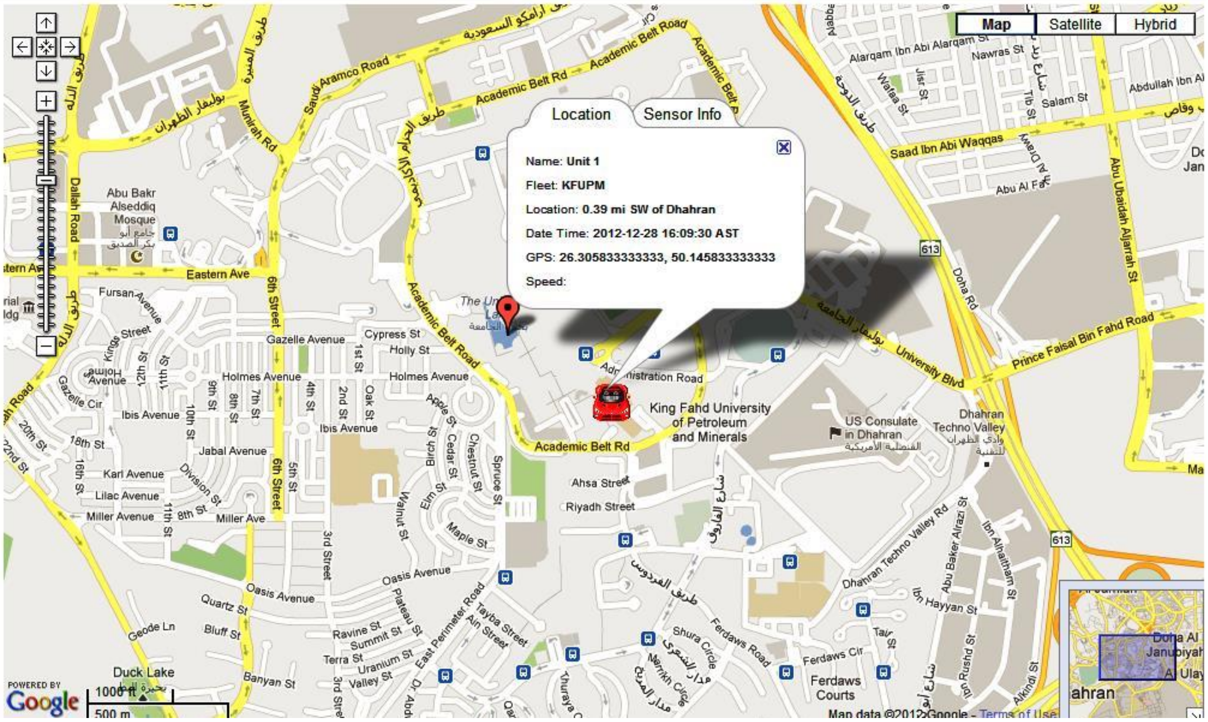


Figure 6.8: Google Maps (Street)

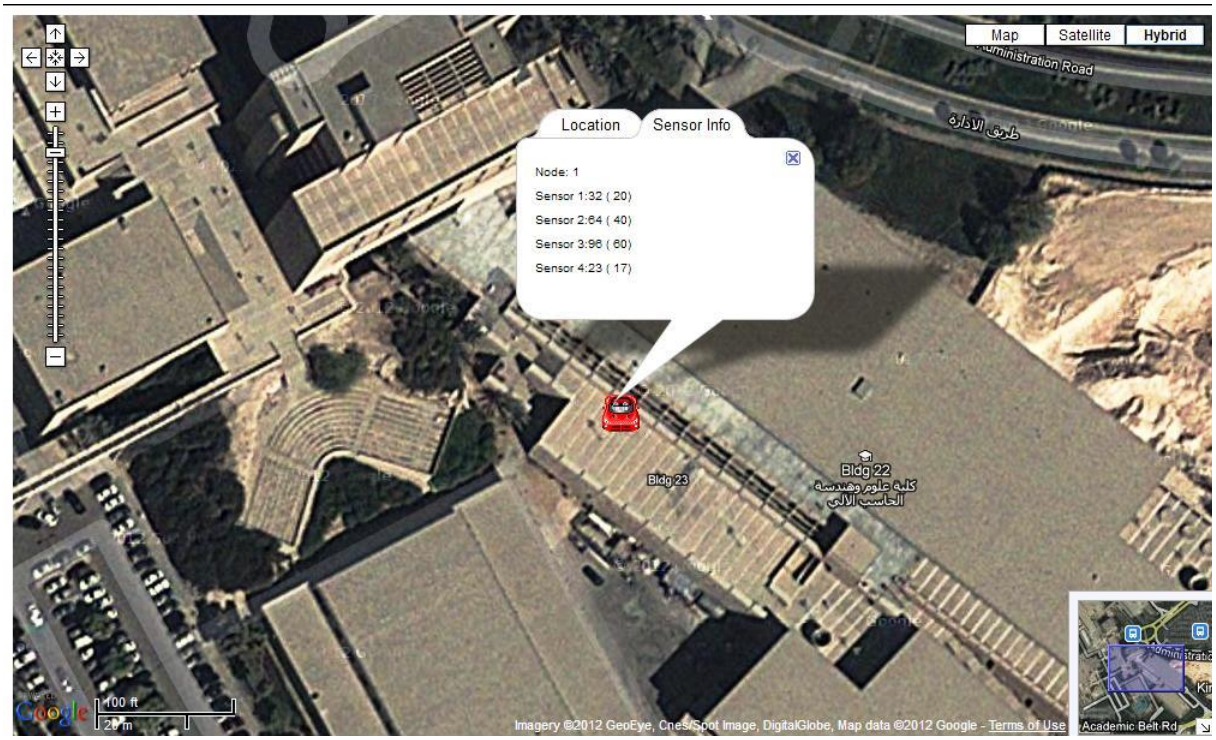


Figure 6.9: Google Maps (Satellite)

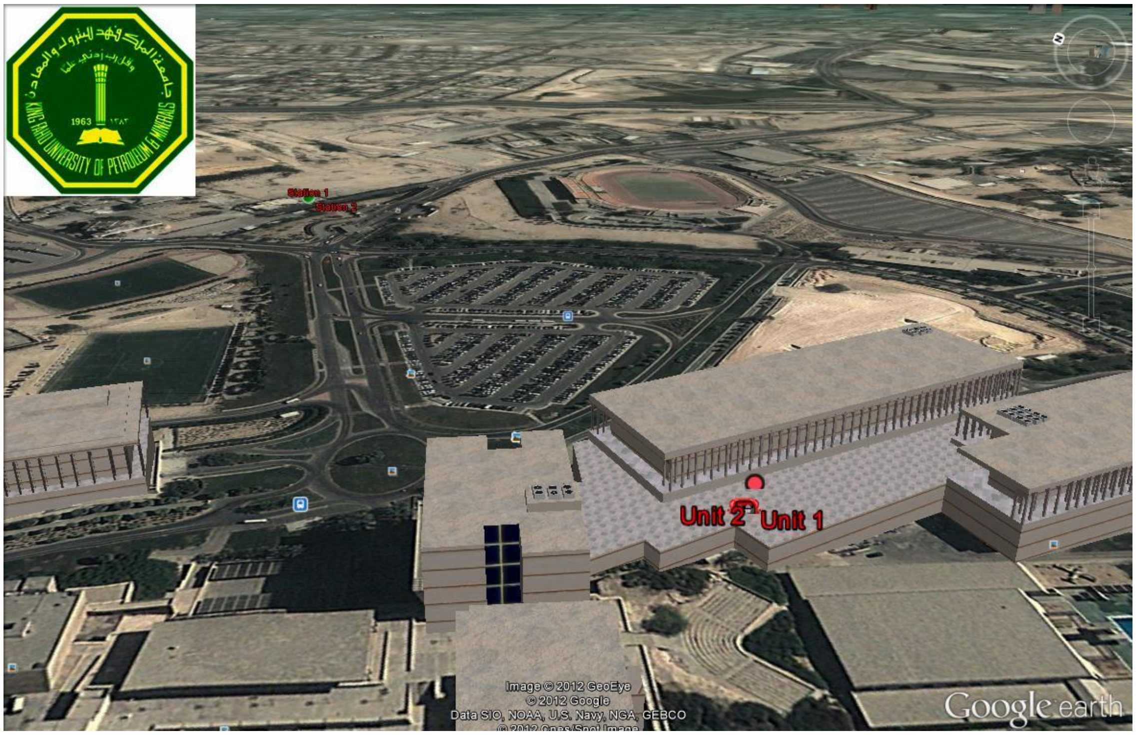


Figure 6.10: Google Earth interface (Zoomed in)

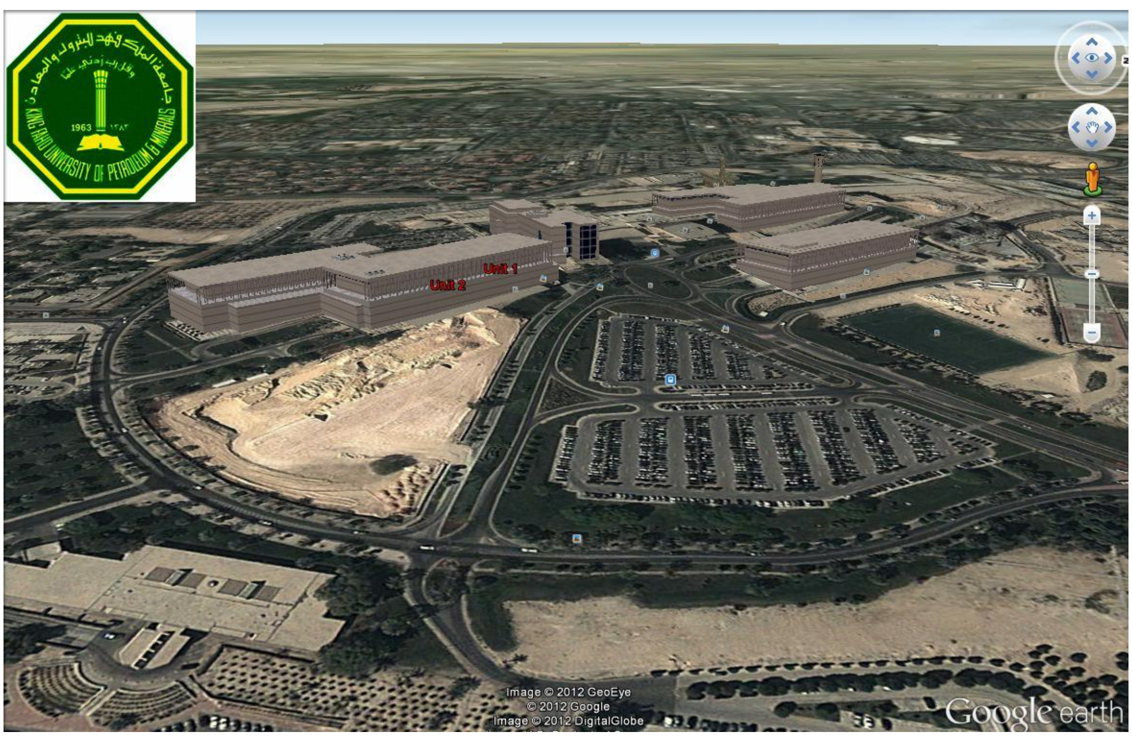


Figure 6.11: Google Earth interface

CHAPTER 7

CONCLUSION AND FUTURE WORK

First, we presented the information related to industrial gases and their properties. Gas detection sensors and technology employed were also discussed. We also provided details of how these gases are monitored and detected in an industrial environment and its significance. We explained the utilization of WSNs in the oil/gas industry and the requirements/challenges of adopting WSN in such environments. Wireless sensors have the ability to monitor plant performance and the operational environment of oil, gas and resource production plants. If effectively deployed, well developed sensor solutions would promote a safe and healthy workplace while simultaneously giving the users the ability to optimize production, and operation safety. Wireless technologies can provide benefits such as improved platform safety, optimized operations, tolerating errors, and reducing operating costs. It is expected that wireless technologies will soon be deployed for cost-effective applications in remote and/or hazardous areas in the oil/gas industries. Recent advancement in industrial wireless sensor network includes availability of low-power gas sensors, e-nose technology, release of industrial wireless communication standards, and research in different aspects of industrial wireless automation. Our review shows that there is not enough research conducted in the gas leakage detection using wireless sensor networks in the oil/gas industry, specially in academia.

There have been significant efforts since 2000 to develop an accurate and reliable range-free localization scheme. Most of the early work assumes an isotropic topology or regular homogeneous node deployment and achieve acceptable performance for most applications. However, real-world deployments are usually in irregular areas with few holes or structures which cause packets to be detoured[64]. This is also true for industrial and urban infrastructure monitoring applications.

The development of a reliable and robust large-scale WSN system requires that the design concepts be checked and optimized before they are implemented and tested on a specific hardware platform. Simulation provides a cost effective and feasible method of examining the correctness and scalability of the system before deployment.

We utilized and extended the Python-based Pymote framework to allow packet level simulation. We implemented modules for propagation, energy consumption and mobility models. We also added graphing and data collection modules to enhance the Pymotes base functionality and modified existing modules for node, network, algorithm and logging to support the extended framework. We also performed a simulation example for a scheme to efficiently utilize EHWSN in an IoT application. The simulation results presented include have topological maps, plots for available energy, bar charts for node displacement and energy consumption and comparison of received and lost packets at the coordinator node.

The focus of this work was to extensively simulate range-free localization algorithms. First, we used topology generator algorithm to generate several isotopic and anisotropic networks based on the desired connectivity, network density and communication range. Then, we employed our extended Pymote framework to carry out very comprehensive localization algorithm simulations to collect several statistics by varying several control parameters. The results are analyzed statistically and visually using interactive charts and plots. We have presented a framework and guidelines which illustrate the importance of systematic and visual analysis of simulation results.

Finally, we proposed an enhancement to the pioneer distance vector or DV-Hop algorithm to estimate nodes localization in anisotropic networks. The recently-proposed algorithms for anisotropic networks provide good estimation but are complex with communication and computational overheads and may be unfeasible or undesirable for low-cost, low-power, location-dependent protocols and applications. Our scheme can reach good accuracy quickly by utilizing simpler, practical and proven DV-Hop-based algorithm. We utilized our Pymote simulation framework to extensively simulate range-free localization algorithms. We generated several isotopic and anisotropic networks based on the desired shape, connectivity, neighbor density and communication range, using our interactive topology generator module. The comprehensive and interactive simulation results obtained have provided statistical and visual analysis and comparison of range-free localization algorithms. Our scheme results in an improved localization accuracy in both anisotropic and isotropic wireless sensor networks of different types, with much faster convergence and low overheads when compared to existing state-of-the-art algorithms.

7.1 Contributions

- A detailed survey of the existing technology related to gas sensors and its monitoring.
- A Study about the feasibility and challenges of utilizing WSNs for gas leakage detection.
- A detailed description of algorithms for determining the location of gas leakage in the WSN-based system.
- Extension of the Python-based Pymote framework to allow packet level simulation.
- Employed our extended simulation framework to carry out very comprehensive localization algorithm simulations and analysis.
- Proposed a new localization scheme which results in improved localization accuracy in anisotropic and isotropic wireless networks of different types, with much faster convergence and low overheads when compared to existing state-of-the-art algorithms.
- A Prototype WSN-based gas leakage detection system with an interactive web application to monitor/analyze the sensor data was designed, built and tested.

- All the skills and expertise gained during this research has been documented and results in several publications.

7.2 Publications

[1] Farrukh Shahzad, Satellite Monitoring of Wireless Sensor Networks (WSNs), Procedia Computer Science, Volume 21, 2013, Pages 479-484, ISSN 1877-0509, http://dx.doi.org/10.1016/j.procs.2013.09.065

[2] F. Shahzad and T. R. Sheltami, An Efficient MAC Scheme in Wireless Sensor Network with Energy Harvesting (EHWSN) for Cloud based Applications," in Local Computer Networks Conference Workshops (LCN Workshops), 2015 IEEE 40th , vol., no., pp.783-788, 26-29 Oct. 2015, doi: 10.1109/LCNW.2015.7365928.

[3] Shahzad F (2015) Extending the Functionality of Pymote: Low Level Protocols and Simulation Result Analysis. Sensor Netw Data Commun 4:125. doi:10.4172/2090-4886.1000125, http://www.omicsonline.com/open-access/extending-the-functionality-of-pymote-low-level-protocols-andsimulation-result-analysis-2090-4886-1000125.php?aid=62590

[4] F. Shahzad, T. R. Sheltami and elhadi Shakshuki, Effect of Network Topology on Localization Algorithm's Performance," in Journal of Ambient Intelligence and Humanized Computing, Accepted Nov. 2015.

[5] F. Shahzad and T. R. Sheltami, Industrial Gases, Detection and Wireless Monitoring in Oil/Gas Industry," 11th Asian Conference on Chemical Sensors (ACCS 2015), Penang, Malaysia, Accepted Nov. 2015.

[6] F. Shahzad and T. R. Sheltami, DV-maxHop: A Fast and Accurate Range-Free Localization Algorithm for Anisotropic Wireless Networks," in the Industrial Electronics, IEEE Transactions on, submitted Nov. 2015.

[7] F. Shahzad, Pymote 2.0: Development of an Interactive Python Framework for Wireless Network Simulations", in the IEEE Internet of Things Journal, under review Dec. 2015.

7.3 Future Directions

As a future work, we will continue building on our simulation framework to include analysis of other network algorithms like routing, clustering, optimization, data gathering, etc. We will also study the effect of noise and signal fading during localization process. Furthermore, we are planning to study, compare and validate other new and up-to-date localization algorithms including mobile anchor-based schemes. We also planing on writing more research paper based on our thesis with some improvements. Some of the areas, we are planing to further study includes determination of optimal $MaxHop$ and reliable anchor distribution schemes. Following papers are in progress:

[8] F. Shahzad and T. R. Sheltami, A Practical Wireless Sensors based Gas Leakage Monitoring System using Satellite Technology," Work in progress, Jan. 2016.

[9] F. Shahzad and T. R. Sheltami, Accurate and Efficient Node Localization Scheme using Multi-objective Optimization," Work in progress, Jan. 2016.

[10] F. Shahzad and T. R. Sheltami, Reliable Anchor distribution for optimal Localization performance in Internet of Things (IoT) applications," Work in progress, Jan. 2016.

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SUMMARY

Strong background in Computer Applications, Databases, Web Technologies/JavaScript, Machine learning, Cloud Computing, Data sciences, System Modeling/Simulation, Data security/cryptography, GIS applications, HMI applications, Wireless Sensors/IoT solutions, M2M/Telematics/Satellite technology.

Active teaching experience in lab, classroom and one-to-one setup. Extensive research experience in design, development and implementation of several projects, individually or in a team. 18+ years' experience in product design, development, engineering, implementation and installation of the original satellite/wireless M2M remote monitoring systems in the Global market.

EDUCATION

PhD (Information and Computer Science)
King Fahd University, Dhahran, Saudi Arabia **Dec. 2015**

- **Took advanced graduate courses in Operating system, Databases, Client Server programming, Computer networks, Computer security, Project management, Cryptography, and Algorithms.**
- Taught undergraduate courses and conducted labs (**C, Java, SQL, Oracle**). Actively involved in ***academic research*** and paper writing activities (see the list of published work)**.**
- Contributed in several projects involving Java applications (UI using swing, JDBC, socket, cryptography). Performed system modeling (UML) and business process model (BPMN 2.0)
- **Dissertation: *Efficient Localization Algorithms for Wireless Gas Leakage Detection in Oil/Gas industry* (presentation: http://slides.com/farrukhshahzad/thesis)**
- **There are about 8 papers related to my PhD research which are either published, under review or work in progress.**

MS (Electrical Engineering) **GPA: 4.0/4.0**
King Fahd University, Dhahran, Saudi Arabia 1996

- Conducted undergraduate labs. Actively involved in academic research and paper writing activities (see the list of published work).

BE (Electrical Engineering) **Grade: 92% (Rank 4/121)**
NED University, Karachi, Pakistan 1992

TEACHING EXPERIENCE

- The research assistant position (during my masters), and recent lecturer-B position at KFUPM (2012 – 2015) has allowed me to gain valuable teaching experience. I have taught Electrical Engineering labs, Computer programming and Database labs and a C programming course for a part of a semester.
- My two decades of industry experience also helps me during teaching. I can relate concepts and theories with practical implications. This motivates students that learning in school will benefit them in their career, whether in industry or academia. I provide details during class how we can apply certain concepts to solve a real-world problem.
- I encourage students to design, develop and implement what they learn in class. This is one of the most practical way to understand some the difficult topics. I myself learn a lot by simulation and coding and ask the students to do the same.
- I have used Blackboard 9.1 and other online tools and videos to explain concepts to my students.
- I have been mentoring undergraduate and junior graduate students in their course and research work.

RESEARCH EXPERIENCE

- My MS and recent PhD studies has sparked my interest in research and technical paper writing activities in association with faculty members.
- During my Master studies in 1995-96, I was able to publish about 10 journal and conference papers with other faculty members including couple of papers in IEEE transactions.
- During the last 20 years, I have worked in industry gaining valuable experience in state-of-the-art technologies. I have worked independently as well as in teams.
- During the last three years, I have been involved in several funded and course projects which results in publication of more than 5 publications. There are 5 more papers under review or work in progress.

AWARDS & COPYRIGHTS

- US copyright holder of four interactive Engineering/Mathematical Software packages.
- Several papers based on simulation from developed software and other research activities are published.
- **Winner in the 4th student conference organized by ministry of higher education in Saudi Arabia in May 2013.**

PUBLICATIONS

Journal/Conferences

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[7] **F. Shahzad**, Atif Z. Khan, "On Java And Its Application For The Of Power System Stability On The World-Wide-Web (WWW)," IEEE Winter Meeting 1998.

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[12] **Farrukh Shahzad**, "State-of-the-art Survey on Cloud Computing Security Challenges, Approaches and Solutions," Procedia Computer Science, Volume 37, 2014, Pages 357-362, ISSN 1877-0509, http://dx.doi.org/10.1016/j.procs.2014.08.053.

[13] **Shahzad, Farrukh**, "Safe haven in the cloud: Secure access controlled file encryption (SAFE) system," in Science and Information Conference, SAI 2015, pp.1329-1334, 28-30 July 2015, doi: 10.1109/SAI.2015.7237315 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7237315&isnumber=7237120.

[14] **Farrukh Shahzad,** Abdullah Devendiran**, "**Disease Outbreak Notification System**,"** accepted for presentation at the Science and Information Conference 2015, July 28-30, 2015, London, UK.

[15] **Shahzad, Farrukh;** Sheltami, Tarek R., "An efficient MAC scheme in wireless sensor network with energy harvesting (EHWSN) for cloud based applications," in Local Computer Networks Conference Workshops (LCN Workshops), 2015 IEEE 40th , vol., no., pp.783-788, 26-29 Oct. 2015, doi: 10.1109/LCNW.2015.7365928.

[16] **F. Shahzad**, T. R. Sheltami and elhadi Shakshuki, "Effect of Network Topology on Localization Algorithm's Performance," in Journal of Ambient Intelligence and Humanized Computing, Accepted Oct 2015.

[17] **F. Shahzad** and T. R. Sheltami, "Industrial Gases, Detection and Wireless Monitoring in Oil/Gas Industry," 11th Asian conference on Chemical Sensors (ACCS 2015), Penang, Malaysia, Accepted Nov. 2015.

[18] **F. Shahzad** and T. R. Sheltami, "DV-maxHop: A Fast and Accurate Range-Free Localization Algorithm for Anisotropic Wireless Networks," in the **Industrial Electronics, IEEE Transactions on**, submitted Dec. 2015.

[19] **F. Shahzad**, “Pymote 2.0: Development of an Interactive Python Framework for Wireless Network Simulations", in the IEEE Internet of Things Journal, under review Dec. 2015.

Others

[20] A PC Based Software Package for Teaching Basic Electrical Engineering Courses, International Journal of Engineering Education, TEMPUS Publication, Germany.

[21] Graphical interpretation of various methods of Power System Transient stability, Electric Power System Research (EPRS) Journal.

[22] Generalized Cases of Equal Area Criterion: Mathematical Formulation and Graphical Representation, International Journal of Power & Energy Systems.

[23] The SMIB Power System Transient stability Assessment: A PC based Graphical Integrated Package, International Power Engineering Conference (IPEC), May 1997.

[24] An Interactive Graphics Program for Comprehending the Equal Area Criterion of Power System Stability, MEPCON, Egypt, pp. 30-35 Jan. 1996.

[25] Equal Area Criterion of Transient Stability: Generalized P-d Diagrams and Equations, MEPCON, Egypt, proceedings pp. 36-40, Jan. 1996.

[26] Presented paper “Development of Interactive Engineering and Educational Software” at 3rd IEEE Technical Exchange Meeting, Dhahran, Saudi Arabia, June 1996.

[27] MS Thesis titled, “Magnetic Field Management in and around Substations”, KFUPM Electrical Engineering, 1996, Advisor: Dr. Farag, Ahmed.

INDUSTRY EXPERIENCE

Jan ‘13–Current **Senior Comms Engineer** **Polestar Global** **(Satellite Monitoring)**

- **Designed and developed Fish Catch electronic form reporting system using Sky wave satellite technology. Application is developed using C# and SQL database for T7A HMI panel. Involved in requirement gathering, design (use case and activity diagrams) and documentation.**
- **Developed several middleware applications in Python to support satellite message processing utilizing Django, RESTful APIs, MongoDB, RabbitMQ/Pika, Celery, SSL socket programming, Amazon cloud services (SNS, cloud watch, SQS, S3 etc.).**

Feb ‘12– Sept ‘12 ***BI Developer*** ***Argo Data Resource Corp, TX*** ***(Software Solution)***

- Extensive use of **Microsoft Business Intelligence tools** to utilize dimension models, data warehouse/marts and OLAP cubes to create complicated, multi-query, parameterize and interactive drill thru reports. Complex report creation utilizing state of the art SSRS tools.
- **Interactive Map based reports utilizing State, County, ZIP code data with analytical datasets.**
- Documentation and functional requirements. Developed comprehensive ETL solutions.

Feb ‘11–Jan ‘12 ***Chief Technology Officer*** ***Voicynx Technology Inc. TX*** ***(VoIP Service Provider)***

- Create and implement VoIP solutions including switch and IP phone configuration and provisioning. Execute business plan for phone service packages to serve residential and business customers.
- Complete company and product websites development (all phases of development lifecycle, including prototyping, development, test, product release and sustaining engineering) using PHP, JavaScript, CSS, API interface (SOAP, WSDL), Goggle Map API, e-commerce, SSL, MySQL, XML and XHTML (LAMP).

Oct ‘03–Nov ‘10 ***Senior Application Engr.*** ***Satamatics/EMS Global Tracking (Remote Sensing/Telematics)***

- **Developed and maintained interactive GIS based website using PHP/JavaScript/ HTML/ MySQL/JDBC/XML, for remote monitoring applications providing 2-way communication for the on-asset satellite terminals/devices/sensors including image/map processing.**
- Developed **GIS** applications using ESRI, Maporama, and Goggle Earth/Map APIs.
- Designed & developed JAVA/JDBC based XML-MODBUS TCP/IP conversion Application on Linux.
- **Implement and Install remote sensing equipment on oil/gas industry’s systems.**
- **Extensively worked on Cathode protection monitoring system using remote sensing technologies.**
- **Involved in technical writing including proposals, design/specification documents.**

Mar ‘97–Oct ‘03 ***Senior Software Engineer*** ***StarTrak LLC Inc., NJ*** ***(Remote Monitoring)***

- **Main Architect in designing and implementing the innovative 2-way Satellite, Cellular and RF communication based remote asset monitoring systems including development of on-asset application, embedded software (firmware, C), message encoding/compression routine and other state-of-the-art algorithms, host server for message decoding and database connectivity (middle ware, Java). Also develop Java Servlets for interactive display of information from remote assets on the web. Application includes interactive maps, Impact monitoring, Reefer monitoring & control, load, pressure and temperature monitoring for trucks and railcars.**
- Developed embedded system software for Intel and TI processor in C.
- Developed interactive Applets, Servlets and Web/Database applications in JAVA and Oracle (JDBC).
- Involved in writing feasibility reports and software specification documents.

Oct '96–Mar '97 ***System Engineer*** ***Eastgate Comm. Inc., NJ*** ***(Telecommunications)***

- Involved in maintenance and smooth operation of UNIX based Network Tele-management System.
- Worked on a project to develop GUI-based database application using Visual FoxPro for NTS under windows '95 by connecting NTS UNIX server with Novell and NT servers.

SOFTWARE SKILLS

Technology	***Experience***	***Description***
Satellite Technology	***15+ years***	***Inmarsat D+, IsatDataPro and IsatM2M, Honeywell terminals, Vistar terminals, Skywave IDP terminal, VSAT, Iridium, Application and on-asset development, HMI forms development***
Networking/ Linux/Unix	**5+ years**	Extensive use of shell scripting/command line tools/vim, application development in Python. MongoDB, RabbitMQ/Pika, Celery, SSL socket programming, Amazon cloud services (SNS, cloudwatch, SQS, S3 etc.)
Business Intelligence	2+ year	SQL Server 2008 R2, T-SQL, Data warehouse/Mart modeling, BIDS, SSMS SSIS/ETL, SSAS/OLAP Cube. SSRS/Report Server, Excel, PowerPivot. Reporting in SharePoint 2010, PerformancePoint and Dash boarding.
SQL Server 2008 R2 & 2012	SSMS, T-SQL, Complex Queries, Views. Database diagrams, Stored Procedure, Backup/Restore, Advanced scripting, Referential Integrity, SQL Server Data Tools	
Data Science	**Completed the following Johns Hopkins University courses offered on Coursera:** The Data Scientist's Toolbox, R Programming, Getting and Cleaning Data, Practical Machine Learning. **Weka, rapid Miner, Cloud data management/security, Classification/clustering, Machine learning algorithms, NoSQL (MongoDB)**	
Microsoft Technology	**C#, Visual Basic, Visual Studio, Office, .Net Compact framework (HMI applications)**	
Languages/Software/ Agile Development	**15+ years**	**Python, Java, C/C++, PHP, SQL, JavaScript, JQuery, R, Pascal, FORTRAN, Agile development utilizing GitHub and Jira**
PHP	**Complete web site development (back and front end) using OO PHP and MySQL.**	
Java	Interactive Applet, Servlets/Application development, **TCP/IP**, **Multi-threading**, **JDBC** connectivity, MODBUS/RS232 applications, security (crypto) applications. AWT/Swing UI	
C/C++	Network programming, Engineering software development, **Embedded/Firmware system programming**, Data analysis and signal processing algorithm development.	
Python	Complex daemon and application development (includes writing extensive unit tests) utilizing encoding/decoding/parsing data, TCP/IP, SSL, MongoDB, RabbitMQ queue, celery, HTTP, REST API, Amazon's AWS (SNS, cloudwatch, SQS, S3 etc.), Scientific/Simulation Apps using numpy, scipy, etc.	
UI development	Web Apps (dynamic HTML, PHP, JavaScript, JQuery), HMI Apps (C#, XAML), NodeJS Apps (JavaScript, jQuery), Ipython	
MySQL/T-SQL/JDBC	10+ years	Complex query/report generation in MySQL/SQL Server (T-SQL)
Web Application/ Web Services/ Framework	10+ years	**XHTML/HML, DHTML, CSS, PHP, Java, JSP, J2EE, JavaScript, jQuery, Angular JS, SOAP, WSDL, API Interface, MySQL, Applets, MVC.**
GIS	**5 years**	**Google maps API, Google Earth/KML, ArcGIS Online, ArcGIS JavaScript API, ESRI Desktop, Maporama,**
IDE	5+ years	**PyCharm**, Eclipse, JCreator, **JDeveloper**, Microsoft Visual Studio
Presentation/UML	15 years	MS Office 2013 (Word, **Excel**, PowerPoint), Visual Studio 2012, Latex
Simulation/Analysis	**5+ years**	**MATLAB, DSP, Software simulation, Algorithm Development, Network Simulation using Python (NumPy, SciPy, matlabplot, Networkx)**
Computer/Data Security	**2 years**	**Cryptography (AES, RSA, HMAC, digital signature, Key generation/exchange), SSL/TLS, Cloud/storage security, Cloud data management/security, OS fingerprinting**

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- **ENGINEER'S TOOLS**: Linear Algebra, Control System Simulations.
- **PSS-EAC**: Graphical package for Power System Transient Stability Analysis.
- **PSS-TSTAB**: Single-machine Infinite Bus Power System Transient Stability Analysis.
- **MMPS-TSTAB**: Multi-machine Power System Load flow and Transient Stability Analysis.

MISC. ACTIVITIES

1. Presented papers "Engineer's Tools" and "Software Simulation" at All Pakistan Student Seminar, Karachi, Pakistan.
2. Participated in the 2nd, 3rd and 4th All Pakistan Software Competition and Exhibition, organized by Dr. A. Q. Khan Research Lab, Islamabad, Pakistan, 1991/92 and 93.
3. Participated in the 1st and 2nd All Pakistan Prof. A.L. Shaikh Intervarsity Software Competition and Exhibition, organized by University of Sindh, Jamshoro, Pakistan, 1993 and 94.

CURRENT PROJECT LIST

1. Disease Outbreak Notification System (DONS) for Saudi Arabia, Sept 2012 – Feb 2014 (Java, swing, JDBC)
2. Designed and developed sand storm detection system using Wireless Sensor networks and Inmarsat satellite technology, Oct. 2012 – March 2013 (Paper accepted in a conference)
3. Open Source Software – Systematic Literature Review, Oct. 2012 – Feb 2014
4. **S**ecure **A**ccess controlled **F**ile **E**ncryption (SAFE) for cloud storage (Java App).
5. Operating System finger printing using Java and machine learning techniques.
6. A Study of Efficient Wireless Gas Sensor Network Based Gas Leakage Detection System.

OTHER PROJECTS

1. Designed and developed data compression & communication software using Huffman code in Visual C, which includes Huffman code generation, encoder and decoder.
2. Implemented several DSP algorithms in MATLAB.
3. Completely design and implement LOGICAL, a software for Logic Design and Switching theory in Visual Basic.
4. The software developed for Single and Three Phase Transformer Design and Performance, is accepted for publication in IEEE-I&CPS Conference, 1997.

REFERENCES

1. Dr. Tarek R. Sheltami (email: tarek@kfupm.edu.sa) +966-13-860-4678
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